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ELECTRIC CONTROL OF FLUID JETS -
THEORY AND APPLICATION TO IMAGE GENERATION

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SUMMARY

A new method for the intensity modulation of ink jets used for recording of electrical signals is studied with respect to its physical properties as well as to its application to facsimile recording. It uses the fact that a liquid jet ejected from a fine nozzle towards a recording paper is dispersed into a spray if an electric field is established near the nozzle. This allows the intensity modulation of the recording trace with frequencies exceeding 100 kHz.

After a general introduction, the basic physical phenomena responsible for the effect employed by this new method are studied in detail and the construction of a suitable device for facsimile recording is described. This device is then used to generate different types of test patterns for an objective determination of the capabilities of the method. To this end the grey scale capabilities, the definition as well as the granularity of the method are measured. The limitations of the image quality found in this way are satisfactorily explained by the basic physical phenomena studied earlier. Finally, examples of facsimile reproductions both in black and white, with grey shades and in colour are given to demonstrate the capabilities of the ink jet device.



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1. GENERAL INTRODUCTION

The rapid growth of technology and its application to every day life have vastly increased the importance of different means of communication and, therefore, much effort has been put into the development of methods suitable to relay information reliably, fast and economically. Much research and development work has been done in the field of graphic information, both in the form of alphanumerical characters and by way of pictorial presentation. Because of the ever increasing volume of this type of information exchange the requirements on the technical methods used to produce written or printed material become more and more stringent.

Especially after World War II two fields in electronics have grown fast because of this fact: telecommunications and data handling by electronic computers. In both of these fields graphic output devices are of crucial importance for their practical value. Further, from the point of view of these output devices, both fields are very similar to each other since they normally convey the information to be displayed in serial transmission. Because of this very similar output devices can be used for both fields.

However, graphical records of signals are not only required in these two areas. For example, it can be pointed out that the recording of electrical voltages is of major importance in all measurement techniques, even if the methods used here are often very different from those named above.

Because of the evident need for new methods to transfer electrical signals into graphic information in many fields of technology, a new device will be investigated in this report which allows the recording of electrical signals on untreated paper by a fast and silent process. This device uses a fine ink jet emerging from a nozzle under high pressure which generates a recording line on a moving paper in front of the nozzle. It will be shown that the trace generated by this ink jet can be intensity modulated with high frequencies by an electrical signal applied to a control electrode which is transversed by the ink jet on its way from the nozzle to the paper. However, before describing the present method, a short general review of graphic methods used in the fields named above and of other ink

jet methods will be given in the following.

1.1. Conventional graphic peripherals

In the telecommunications as well as in data handling by computers output devices capable of producing alphanumeric characters are used predominantly at present. Most of these devices employ electromechanical systems as e.g. the conventional teleprinter or line printer (Borne 1968, Carrol et al. 1970). Electromechanical systems can even be used to generate computer controlled graphs by X-Y-plotters, of which the CALCOMP-plotter is maybe the best known example. All these devices have the advantage of using inexpensive, untreated paper and are able to produce carbon copies. They are, however, relatively slow and noisy and do not lend themselves easily to the production of coloured records.

Because of these disadvantages, other methods have been developed which have recently been reviewed by Paynter (1971). In contrast to electromechanical devices these methods mostly do not use mechanical contact between the recording device and the paper because of which they are often classified as non-impact methods. Therefore, nearly all of them lack the ability to produce copies. Since it is not possible to give an exhaustive review of these methods here, only a few examples will be mentioned to discuss their relative merits.

First of all, the photographic process is obviously ideally suited for the present purpose because of its speed, high resolution, large density range and colour capability (Wurtz 1969). However, it is an expensive medium and usually requires processing, which makes it impossible to inspect the record immediately after the recording. Alternatively, electrostatic processes using the Xerox or ZnO_2 principle have been developed (Lessing 1969) which again require processing and do not have colour capabilities. Further, the Xerox process does not reproduce grey shades too well and the ZnO_2 method requires special paper. - Especially for computer output devices but also for recorders of fast electrical signals, paper covered by a highly insulating plastic layer is used, the surface of which is charged either by special cathode ray tubes or by a large number of small electrodes positioned very close to the paper. By processing in an insulating fluid containing carbon black, the charged areas of such paper

can be made visible in a way similar to that of the ZnO_2 process (R.G. Sweet 1968, Wurtz 1969, Hurst 1970). Even here, special paper is required and no colours can be produced. Further, the recording equipment itself is of relatively high complexity. Many other methods could be named, e.g. the Kalvar film process (Wurtz 1969), the Alfax electrochemical method (Alden 1966) or the use of small sparks of electric current damaging the surface of special types of paper (Dibbern 1970), but all of these require special paper and do not have colour capabilities. The only exception from this seems to be the electrostatic printing process described by Childress (1966), which, however, lends itself only to large volume printing.

1.2. Ink jet devices

Because of the situation described above great interest is directed towards the application of fine ink jets to different graphic problems. Such ink jets would be able to print silently on any type of paper and are relatively easy to generate because of which they should offer an economic solution to many graphic problems. Further, ink jet recorders allow an immediate inspection of the record, do not require any processing and may also be used to generate coloured records. Because of this appreciable effort was put into the development of ink jet systems already before the second world war, an example of which is given by the work of Schröter (1932) and Hansell (1933). However, no practicable system could be demonstrated at that time.

The first important step in the development of ink jet techniques was made by R. Elmqvist by designing an ink jet oscillograph in which a fine jet of ink is used for the recording of electrical signals of frequencies up to about 1000 Hz (Elmqvist 1951, Sima 1966). Due to their paper economy as well as to the fact, that the record is immediately accessible, these oscillographs are widely used in European hospitals for the recording of physiological parameters such as ECG, EEG and the like.

However, in many other applications a high recording speed is required. Therefore, different methods were developed to control an ink jet by electrical signals (Stone 1971). Except in a method recently constructed by Stemme (1971) the ink jet is influenced directly by the electrical signal in these methods. In principle, they can be divided into three diffe-

rent groups, which will be shortly reviewed in the following.

C.R. Winston produced the ink jet by a high electric field generated by an electrode V directly in front of a nozzle N (Fig. 1:1) having a diameter of about 300 μm (Winston 1962, Kolb 1966). This ink jet consists of small, electrically charged drops which transverse an aperture in the electrode V and proceed towards the recording paper which is kept at a suitable potential and situated about 1 cm from the nozzle N. On their way to the recording paper, the ink drops traverse a vertical and a horizontal pair of deflection plates P_v and P_h . If suitable voltages are applied to these plates, the stream of ink drops can be deflected in a similar way as the electron beam in the cathode ray tube, because of which alphanumeric characters can be traced on the paper in this way. E. Ascoli (1968) has developed a very similar system for producing the jet. Both systems are used as printing heads in teleprinters.

Compared with the two other ink jet methods described below, the generation of the ink jet by electric forces used here has the advantage that the ink flow from the nozzle can conveniently be cut off immediately after the printing of one character. However, certain difficulties may be experienced because of the high voltages employed in the presence of charged liquid drops, which can settle on insulators supporting the electrodes and thereby causing short circuits. Dirt adhering to the nozzle may also disturb the jet forming process (Ascoli 1968). Further, the printing speed is relatively slow compared to the character quality achieved. This is due to the relatively small forces creating the jet and the fact that these forces have to accelerate the mechanical mass of the ink drops during the printing process.

This difficulty is circumvented by the method proposed by Sweet (1964, 1965) who created the jet by forcing ink under high pressure through a nozzle with a diameter of about 30 μm . As shown in Fig. 1:2 the jet breaks up into a train of discrete droplets shortly after leaving the nozzle N. At this point of drop formation a ring formed control electrode E is situated to which the signal voltage is connected. Due to electric influence the jet is charged roughly proportional to the voltage on this electrode E at the point of drop formation. Because of this, each drop formed at that point leaves the continuous jet with an electric charge proportional to the signal voltage at the instant when the drop was being formed. These drops then pass through a high transversal DC field maintained between

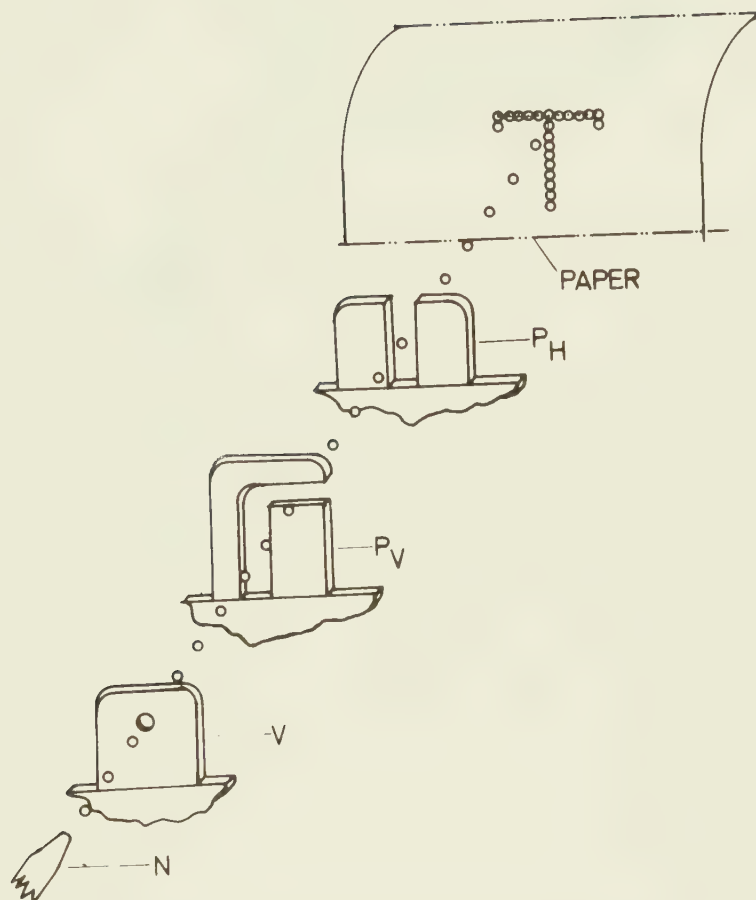


Fig. 1:1. Winston's method for the electric generation and control of an ink jet.

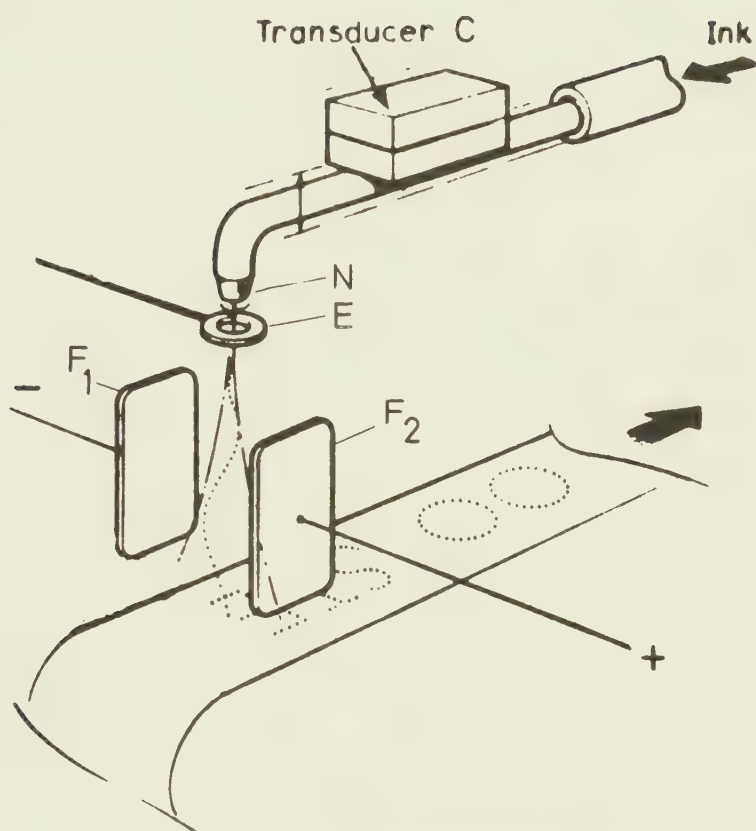


Fig. 1:2. Sweet's method for the electric control of an ink jet.

the electrodes F_1 and F_2 producing a deflection of the drops proportional to their charge. The paper moves continuously at right angles to the deflection of the droplets, thereby producing the other axis of the deflection.

To ensure that the drop deflection depends on the drop charge only, the mass of the individual drops has to be constant. This is achieved by vibrating the nozzle with a transducer C as indicated in Fig. 1:2, thereby controlling the otherwise spontaneous drop formation process. With a nozzle of 35 μm the frequency of the mechanical vibrations is about 100 kHz thus forming 100000 drops of nearly the same size.

Originally, Sweet (1965) has used this method in an oscillograph for recording of electrical signals. Later, Lewis et al. (1967) applied the method to the printing of characters as indicated in Fig. 1:2. Using the same principle many other alternatives were proposed, e.g. by Loughren (1968), Taylor (1970) and others.

The advantage of the Sweet method lies in the fact, that the path of the ink drops and thereby their final position on the paper is determined by their charge only. This charge, however, is applied to the drops by a purely electrical process. Since no mechanical masses are accelerated during this phase of the process, it is much faster than the method described earlier. It will be shown in chapter 2 that the maximum drop formation frequency and thus also the upper frequency limit of the method is inversely proportional to the diameter of the jet. Thus for high printing speeds small nozzles should be used.

However, with nozzles smaller than 30 μm certain difficulties are encountered because of which drop formation frequencies above 100 kHz cannot be used in a reliable apparatus. Further, even in the Sweet method relatively complicated electrode structures and high electric fields are used to deflect the drops. As before the presence of charged drops may lead to insulation breakdown. Further, in character printing apparatus the control signal voltage has to be perfectly synchronized with the drop formation process. This requires a high constancy of ink jet parameters as e.g. pressure, viscosity and surface tension of the ink.

Because of these difficulties as well as the relatively low speed of the Sweet process a third method to control an ink jet by an electric signal will be investigated in this paper. This method uses a well-known

property of fluid jets which was already observed by Abbé Nollet in 1749 (cf. Fig. 1:3). Even Sweet (1964) described that the fine ink jet in his apparatus was dispersed into a spray of charged drops, if the voltage of the control electrode E was raised above a few hundred volts. The reason for this phenomenon lies in the fact, that highly charged drops interact with each other. Thus, if all the drops have the same charge the electric repulsion between adjacent drops may become so large that the linear jet is broken up and transformed into a spray as shown in Fig. 1:3, where water flows from different containers which are kept at high electric potential.

In this report a method is studied which uses this spray formation for the intensity modulation of a recording ink jet with frequencies of more than 100 kHz. In chapter 2 the physical mechanism responsible for the properties of the device is investigated and its construction described, while chapters 3, 5, 6 and 7 deal with the quality of images reproduced by it. Chapter 4 describes an apparatus for the reproduction of different kinds of originals by the device, the result of which is finally discussed in chapter 8.

An earlier version of the ink jet method studied here has been described by Hertz et al. (1967) and applications of this method to different recording problems were published by Hertz et al. (1969), Ernbo et al. (1969) and Ernbo (1972). A recent review article is given by Hertz et al. (1972) and a study of the mechanism of the ink jet device has been made by Månsson (1972).



Fig. 1:3. Copper-plate engraving from the Deutsches Museum, Munich: Abbé Nollet studying electrostatic phenomena produced by running water (1749).

2. THE INTENSITY MODULATION PROCESS

2.1. Introduction

The intensity modulation of recording ink jets (Hertz et al. 1967, 1972) which is described in detail in the following involves forming, charging and mutual electrostatic repulsion of the small fluid drops of a high speed liquid jet and finally a partial interception of the repelled drops. The principle of this process is demonstrated by Fig. 2:1.

In Fig. 2:1a a fine liquid jet J is produced by forcing ink under high pressure through the nozzle N. The jet is directed towards the recording paper. If this paper moves continuously, a recording trace is obtained on the paper as shown in Fig. 2:1a. Directly after leaving the nozzle, the ink jet traverses a ring shaped electrode E, which is connected to a voltage source U. The other side of the source U is connected to the somewhat conductive ink in the tube leading to the nozzle.

If a voltage of sufficient magnitude is generated by the voltage source, it is found that the ink jet is transformed into a spray of fine droplets as shown in Fig. 2:1b. Since the ink jet is dispersed, obviously no recording trace is obtained on the paper during the time the voltage is maintained. Thus, by controlling the voltage of the electrode E in a suitable way the ink jet can be switched on and off, resulting in an on-off intensity modulation of the trace on the paper. It will be shown below that the upper frequency limit for this modulation is quite high because of which this method for the intensity modulation of a recording trace may find interesting applications in different fields.

To prevent the drops of the spray from reaching the recording paper where they would create an objectionable background, a diaphragm D can be placed directly in front of the recording paper as shown in Fig. 2:1c. While the undisturbed jet can reach the recording paper through the aperture A in the diaphragm, the drops of the spray are intercepted. Further, since it can be shown that the solid angle formed by the spray can be controlled by the signal voltage applied to the electrode E, even the density (grey shade) of the trace can be determined.

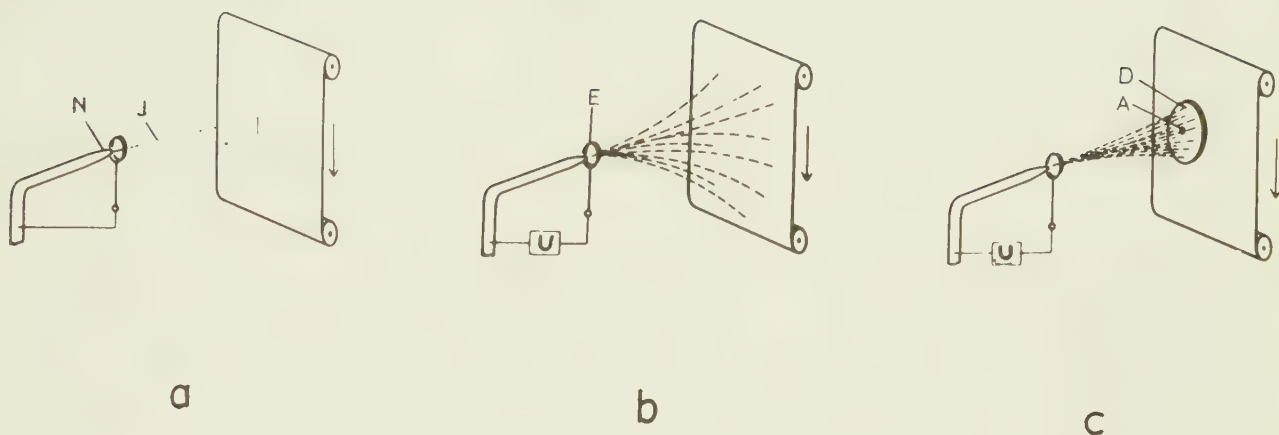


Fig. 2:1a. By forcing ink under high pressure through the fine nozzle N, an ink jet J is formed which almost immediately disintegrates into drops. The jet generates a trace on the recording paper.

- b. This jet can be transformed into a spray of charged drops by applying a suitable voltage U to the control electrode E. In that case no trace is obtained on the paper.
- c. This allows an intensity modulation of the trace since the drops of the spray can be intercepted by a diaphragm D.

Because of the many applications this process may find in different fields of technology it is of great interest to investigate the fundamental physical properties of electrically controlled fluid jets. In this way it would be possible to determine the capabilities as well as the limitations of the method. Because of this, different aspects of the physical process will be studied in this chapter using fluid jets with diameters from 7 μm to 20 μm and jet velocities between 20 and 50 m/s.

2.2. Drop formation

2.2.1. Spontaneous mode

If a low viscosity liquid is forced through a capillary tube with sufficient velocity, so that a jet issues from the capillary tip, this jet can be observed to disintegrate into a sequence of drops at a certain distance from the tip. These drops are relatively random in size and not quite equidistant. In Fig. 2:2 such a drop formation is demonstrated for a 10 μm -jet with a velocity of 20 m/s. To get a well defined micro-photograph of this rapid phenomenon, the jet under the microscope was illuminated with a giant laser pulse of a duration of 40 ns. The technique for this is described by Månsson (1972).

Lord Rayleigh (1879) theoretically investigated the behaviour of a cylindrical column or jet of non-viscous liquid and found it to be unstable under the action of surface tension. Further he found that a small axisymmetrical sinusoidal variation of the diameter which is impressed on the jet grows exponentially with time until the jet disintegrates into drops if the wavelength of the disturbance is larger than the circumference of the jet. The rate of this growth varies with the wavelength and has a maximum for a wavelength which is 4.5 times the jet diameter.

In the case photographed in Fig. 2:2 no disturbances were impressed upon the jet and the spontaneous disintegration in this case is determined by the range of wavelengths which causes the instability most rapidly. Consequently, according to theory, the separation between the drops should on the average be 4.5 times the jet diameter. This is verified by the photograph and the inserted length scale.

According to Weber (1931) and Haenlein (1931) the disintegration into

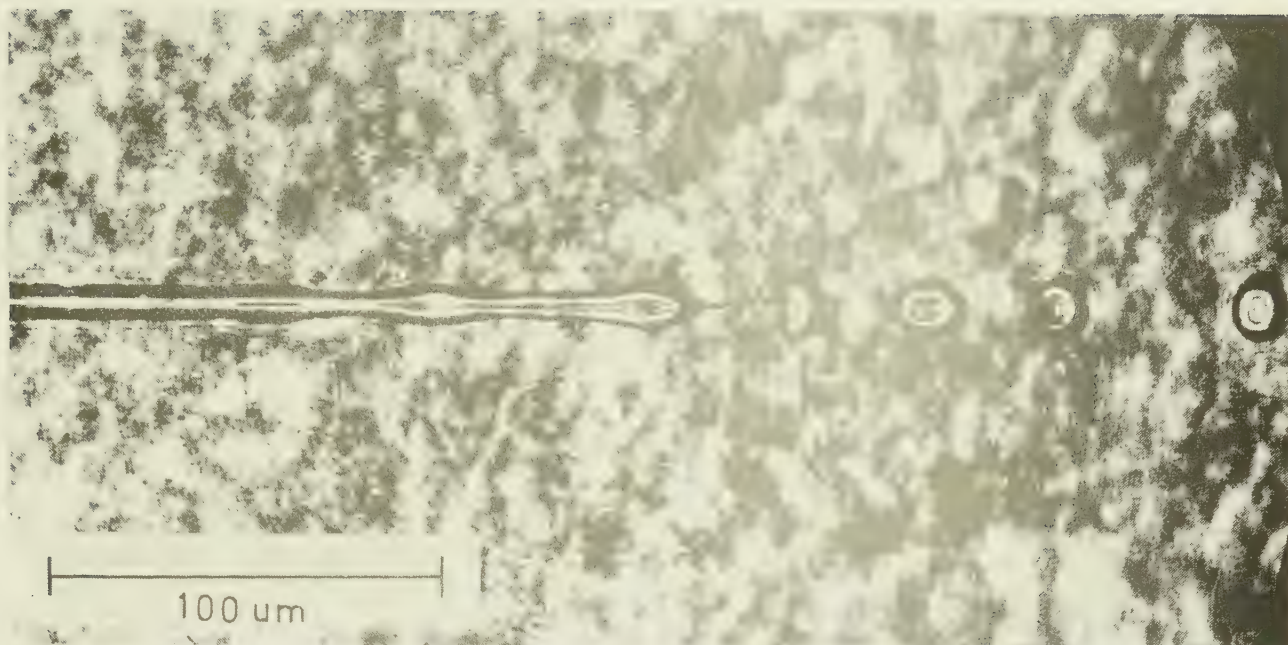


Fig. 2:2. Spontaneous drop formation of a 10 μm liquid jet traveling at 20 m/s about 1 millimeter from the nozzle.

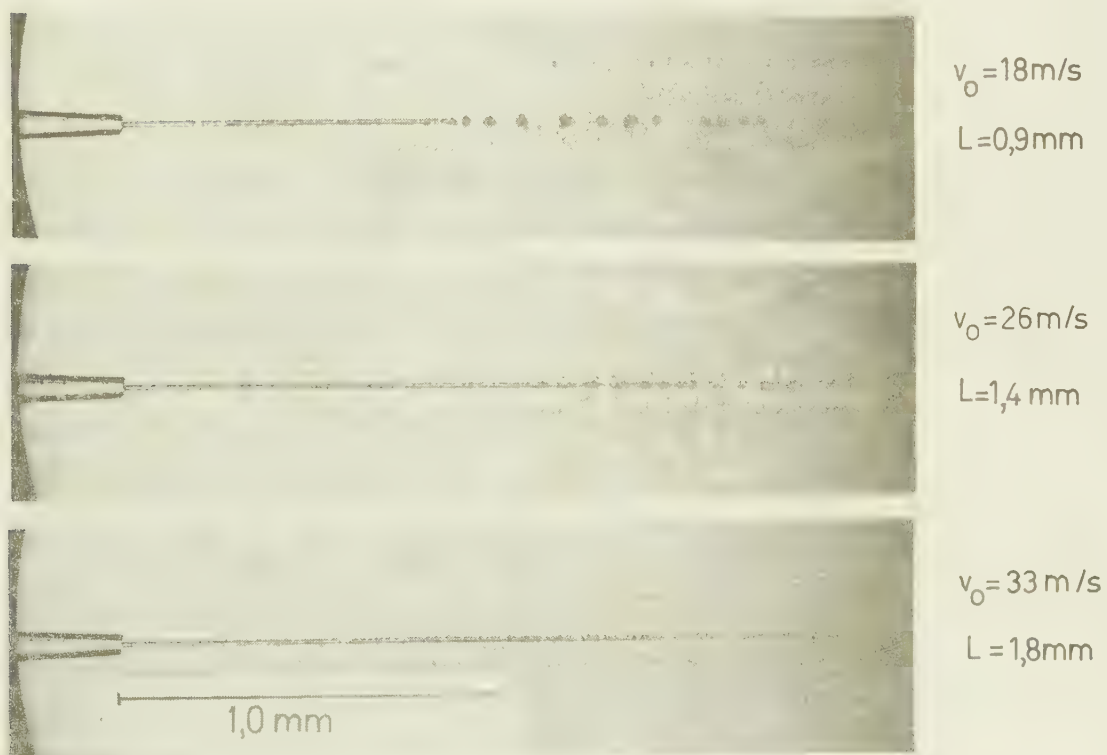


Fig. 2:3. Position of point of drop formation of a 10 μm jet for different ink jet velocities.

droplets would occur at a distance L from the nozzle for a low viscosity jet where

$$L = 12.0 \cdot v_o \left(\frac{d_o^3 \cdot \rho}{\sigma} \right)^{1/2} \quad (1)$$

in which v_o is the mean outflow jet velocity, d_o the nozzle diameter, ρ the liquid density and σ the surface tension.

In the case of a $10 \mu\text{m}$ capillary and the ink being used with:

$$\begin{aligned} d_o &= 10^{-5} \text{ m} \\ \rho &= 1.05 \cdot 10^3 \text{ kg/m}^3 \\ \sigma &= 73 \cdot 10^{-3} \text{ N/m} \end{aligned}$$

we get from equation (1)

$$L \approx v_o \cdot 0.045 \cdot 10^{-3} \text{ m}.$$

For a velocity $v_o = 40 \text{ m/s}$ this results in a numerical value of L of 1.8 mm . Experimentally L has been determined to 2.3 mm for this velocity. The approximate proportionality of L versus jet velocity is illustrated by Fig. 2:3 where a jet of diameter $10 \mu\text{m}$ and 3 different velocities is photographed. The velocities were obtained by a determination of the volume ejected per time unit.

2.2.2. Controlled mode

In order to obtain a more regular drop formation it is possible to impress small periodic variations of the diameter along the continuous part of the jet, as mentioned above. If these variations are larger than the spontaneously caused disturbances they predominate and cause the disintegration of the jet into equal sized drops. For a more detailed investigation of this possibility the presentation of some basic relations between the parameters of the jet is required.

In Fig. 2:4 a jet with a diameter of d_o is issued with a velocity of v_o and is disintegrated into equidistant drops of diameter d_d with a distance between their centres of λ . To this jet a sinusoidal disturbance resulting in an initial peak variation of the jet diameter of $\Delta d(0)$ is impressed where

$$\Delta d(0) = d_{\max}(0) - d_{\min}(0)$$

The peak variation of the jet diameter at time t is then given by

$$\Delta d(t) = d_{\max}(t) - d_{\min}(t)$$

Lord Rayleigh (1879) showed that $\Delta d(t)$ is growing with time according to the

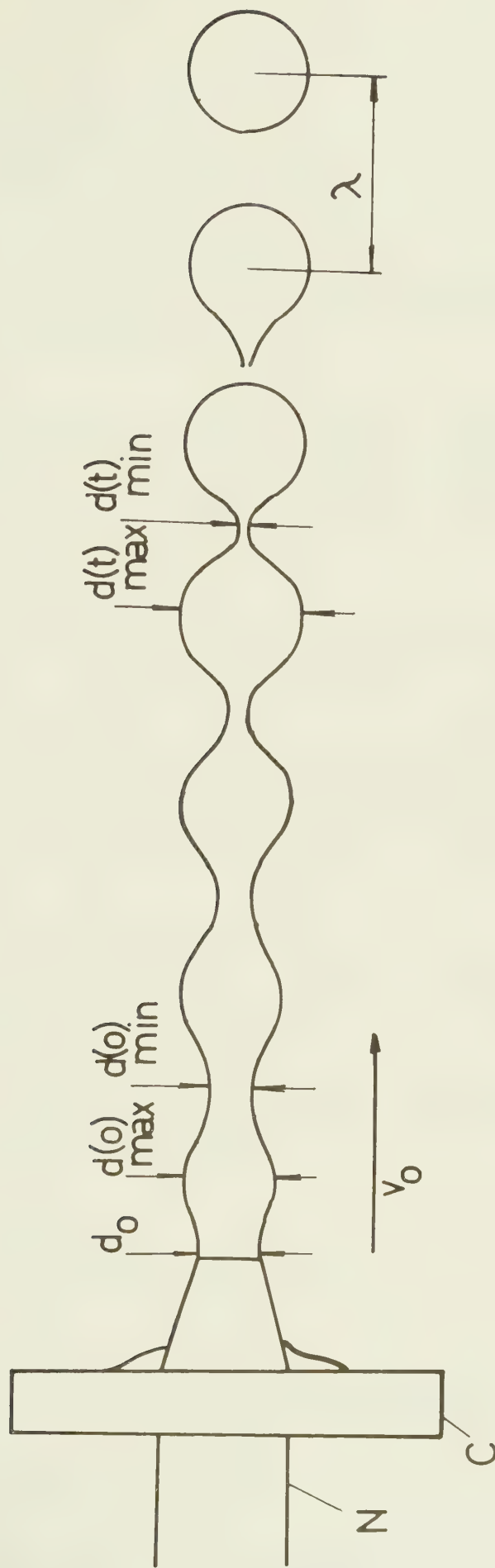


Fig. 2:4. Principle of controlled drop formation.
For details see text.

relation:

$$\Delta d(t) = \Delta d(0) \cdot e^{t/T} \quad (2)$$

where $T = \frac{1}{I} (\rho \cdot d_o^3 / 8\sigma)^{1/2}$ (3)

in which ρ = density of the liquid

σ = surface tension of the liquid

and $I = I(\lambda/d_o)$ = jet instability factor. The function $I(\lambda/d_o)$ was derived by Lord Rayleigh and is plotted in Fig. 2:5.

From the relation (2), (3) and Fig. 2:5 it is evident that the wavelength of the disturbance must exceed πd_o if growth of the disturbance would be able to occur. Since the relation between the frequency of drop formation and the wavelength is given by

$$f_d = \frac{v_o}{\lambda} \quad (4)$$

the maximum drop formation rate theoretically occurs for $\lambda_{min} = \pi \cdot d_o$:

$$f_{d_{max}} = \frac{v_o}{\pi d_o} \quad (4a)$$

Since the "instability factor" I has its maximum for $\lambda = 4.5 d_o$, the time constant T has its minimum and consequently the maximum rate of growth occurs for a drop formation frequency of:

$$f_d(\text{maximum rate of growth}) = \frac{v_o}{4.5 d_o} \quad (4b)$$

As mentioned in connection with Fig. 2:2 this is the average drop formation frequency when no disturbance is applied.

As evidenced from the principle of volume conservation per unit length of the jet the volume of a drop V_d is:

$$V_d = \frac{\pi d_o^2 \lambda}{4} = \frac{\pi d_d^3}{6} \quad (5)$$

and consequently the diameter of a drop d_d :

$$d_d = \left(\frac{3}{2} d_o^2 \lambda\right)^{1/3} \quad (6)$$

Combining (4a) and (6) gives the minimum drop diameter $d_{d_{min}}$:

$$d_{d_{min}} = d_o \left(\frac{3}{2} \cdot \pi\right)^{1/3} = 1.68 d_o \quad (6a)$$

and combining (4b) and (6) gives the drop diameter d_d for maximum rate of growth:

$$d_d(\text{max. rate of growth}) = d_o \left(\frac{3}{2} \cdot 4.5\right)^{1/3} = 1.89 d_o \quad (6b)$$

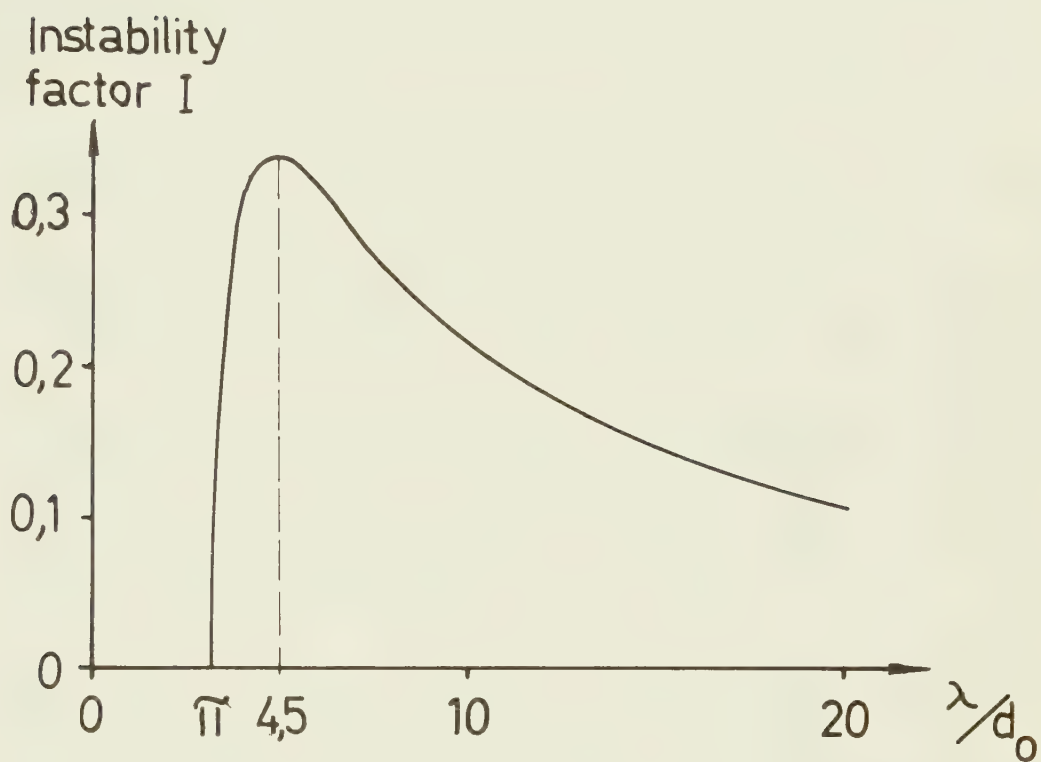


Fig. 2:5. For explanation see text.

Since the intensity modulation process requires a high, regular drop formation rate in order to obtain a high upper frequency limit and a high charge to mass ratio of the drops, the relation (4a) will be of further interest. Schneider and Hendricks (1964) and Lindblad and Schneider (1965) experimentally verified (4a) by showing that λ must exceed $\approx 3.5 d_0$ for stable synchronization of droplets for jet diameters larger than $25 \mu\text{m}$. However, we considered it necessary to extend this investigation to the range of the smaller jet diameters normally used in the ink jet method presented in this report ($7 - 20 \mu\text{m}$).

For this purpose a series of photographs were made by Månsson (1972) of the drop formation. In that case mechanical vibrations were applied by means of a piezoelectric crystal C (PZT-crystal, Brush Clevite Crystal Company) which was glued to the capillary N as shown in Fig. 2:4. No attempts to determine the ultrasonic energy conferred to the jet have been made due to the difficulties with crystal resonances, undefined acoustic impedance due to the quality of the glueing of the capillary to the crystal and the relatively individual shape of the glass capillaries. However, in no case the voltage applied to the crystal exceeded $3 V_{\text{eff}}$.

Some examples of the results of this photographic investigation are given in Fig. 2:6 in which a series of photographs show a $10 \mu\text{m}$ jet with an exit velocity of about 40 m/s with increasing drop formation frequency. The lowest possible λ/d_0 -ratio for various nozzle diameters was determined by varying the crystal frequency in steps of 50 kc/s , beginning with the theoretical frequency for spontaneous drop formation and extending the final frequency securely above the theoretical maximum given by (4a). For every frequency a microphotograph was obtained in which the eventual existence of a regular drop formation was easily established.

The results from the determination of the lowest possible λ/d_0 -ratio for various nozzle diameters are presented in Table 2.1. In some of these experiments fine holes in metal plates, normally used as electron microscope apertures, served as nozzles. The type of nozzle used is given in the first and second columns. The measurement of the jet velocity was made by measuring the distance in the photographs between drops generated by a known frequency of the mechanical vibration f_d . The predicted and theoretical values of λ/d_0 are based on the assumption that a contraction of the jet takes place when it leaves the nozzle. For the value of the contraction factor (the ratio between the ejected jet diameter and the nozzle dia-

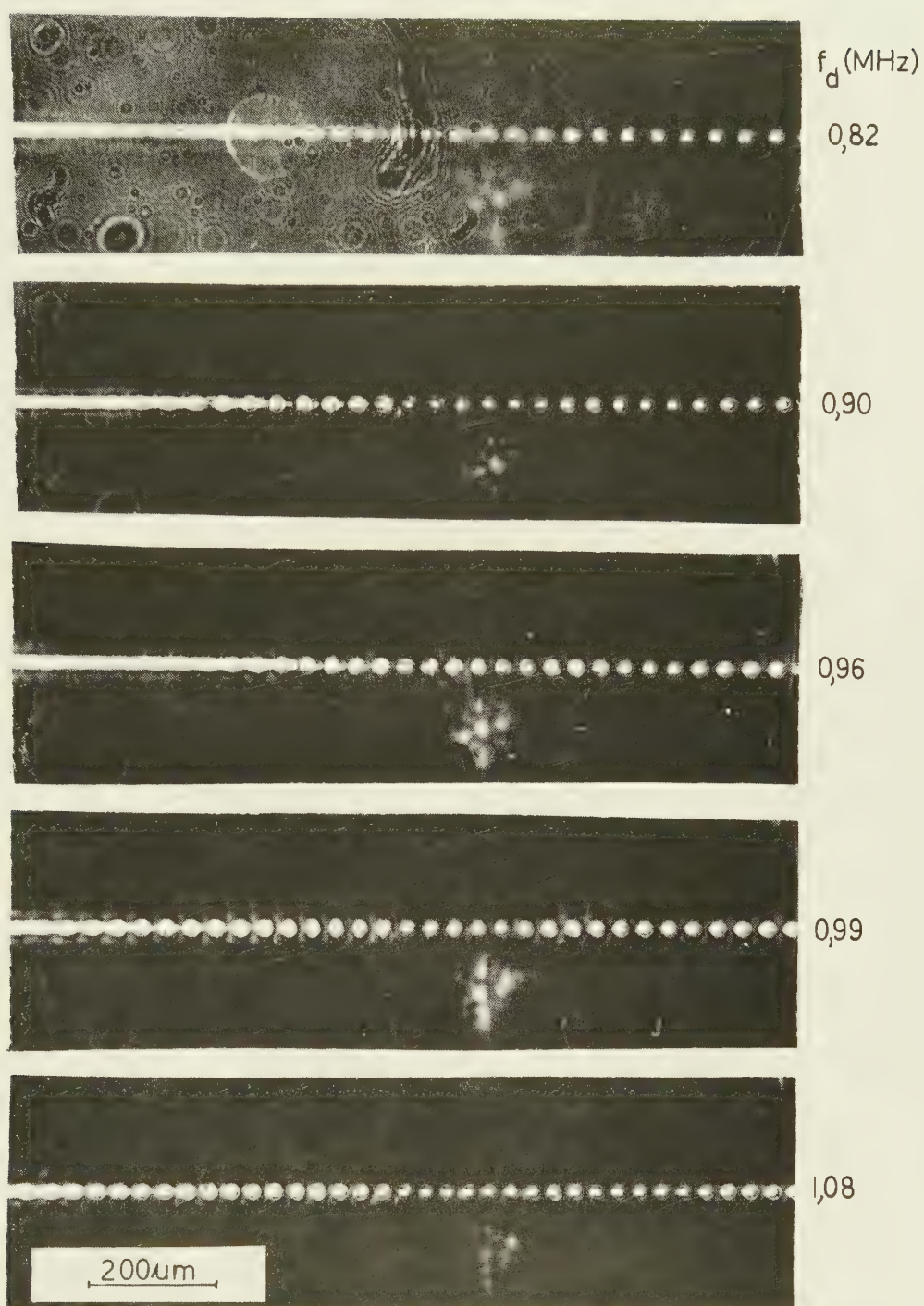


Fig. 2:6. Controlled drop formation of a 10 μm jet travelling at 40 m/s at different frequencies of the mechanical vibrations.

Type of nozzle Material	Diam. d_o (μm)	Jet Velocity v_o (m/s)	Vibration frequency $f_{d_{\text{max}}}$ (MHz)	$\left(\frac{\lambda}{kd_o}\right)_{\text{min}}$ (theor.)	$\left(\frac{\lambda}{kd_o}\right)_{\text{min}}$ (pre- dicted)	$\left(\frac{\lambda}{kd_o}\right)_{\text{min}}$ (exp.)	Corresponding volume of one drop (exp.) ($\cdot 10^6 \text{ mm}^3$)
Glass	10	39	1.40	π	3.5	3.2	1.67
Platinum	10	47	1.60	"	"	3.4	1.73
Platinum	15	36	0.75	"	"	3.7	6.08
Platinum	20	31	0.50	"	"	3.6	14.3

Table 2.1.

meter) Harmon's (1955) theoretical value of $k = 0.87$ has been used.

In the last column of the table the minimum volume of one drop is given for different nozzle diameters. This value is of interest because it constitutes the definite lower limit for the liquid volume, which can be controlled by the intensity modulation process. The results show that this volume is approximately proportional to the third power of the nozzle diameter which is theoretically expected from (5) and (6a).

Another consequence of the application of the mechanical vibrations causing the drop formation is that the disintegration into droplets will occur closer to the capillary tip than the distance L given by equation (1). The reason for this is obvious, since the applied disturbances must be strong enough to predominate over the spontaneous disturbances at the jet exit and cause the drop formation more rapidly than those.

In practice observations have shown that the distance from the nozzle to the drop formation point may vary from approximately 0.5 mm to 2.3 mm for a $10\text{ }\mu\text{m}$ jet with an exit velocity of 40 m/s having its drop formation controlled by means of mechanical vibrations from a PZT-crystal as described above. This displacement of the drop formation point may be important in certain cases, since the charging of the drops occurs at this point.

2.3. Charging of the drops

The application of the voltage U between the ink jet and the cylinder formed electrode E in Fig. 2:7 assures a charging of the drops by electrostatic influence. The voltage induces a charge on the continuous part of the conducting jet, extending from the nozzle to the point of drop formation. Every drop carries away a part of this charge, proportional to the product of the voltage and the capacitance between the electrode and the drop in the moment of its formation. Since the drops are of approximately equal size, the charge of the drops is equal, at least when the drop formation is controlled by means of mechanical vibrations.

This simple dependence of the drop charge on the voltage applied to the control electrode is shown by Fig. 2:8 where the jet current I_j versus the control voltage U for a $10\text{ }\mu\text{m}$ jet is plotted. It verifies the linear dependence of I_j versus U until a certain limiting voltage U_1 is reached where

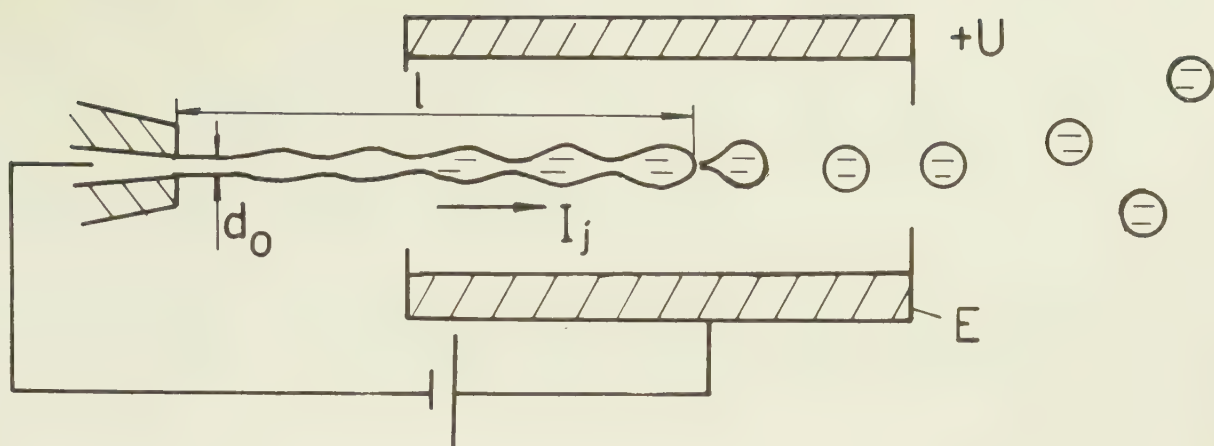


Fig. 2:7. Charging of fluid drops by voltage U on control electrode E .

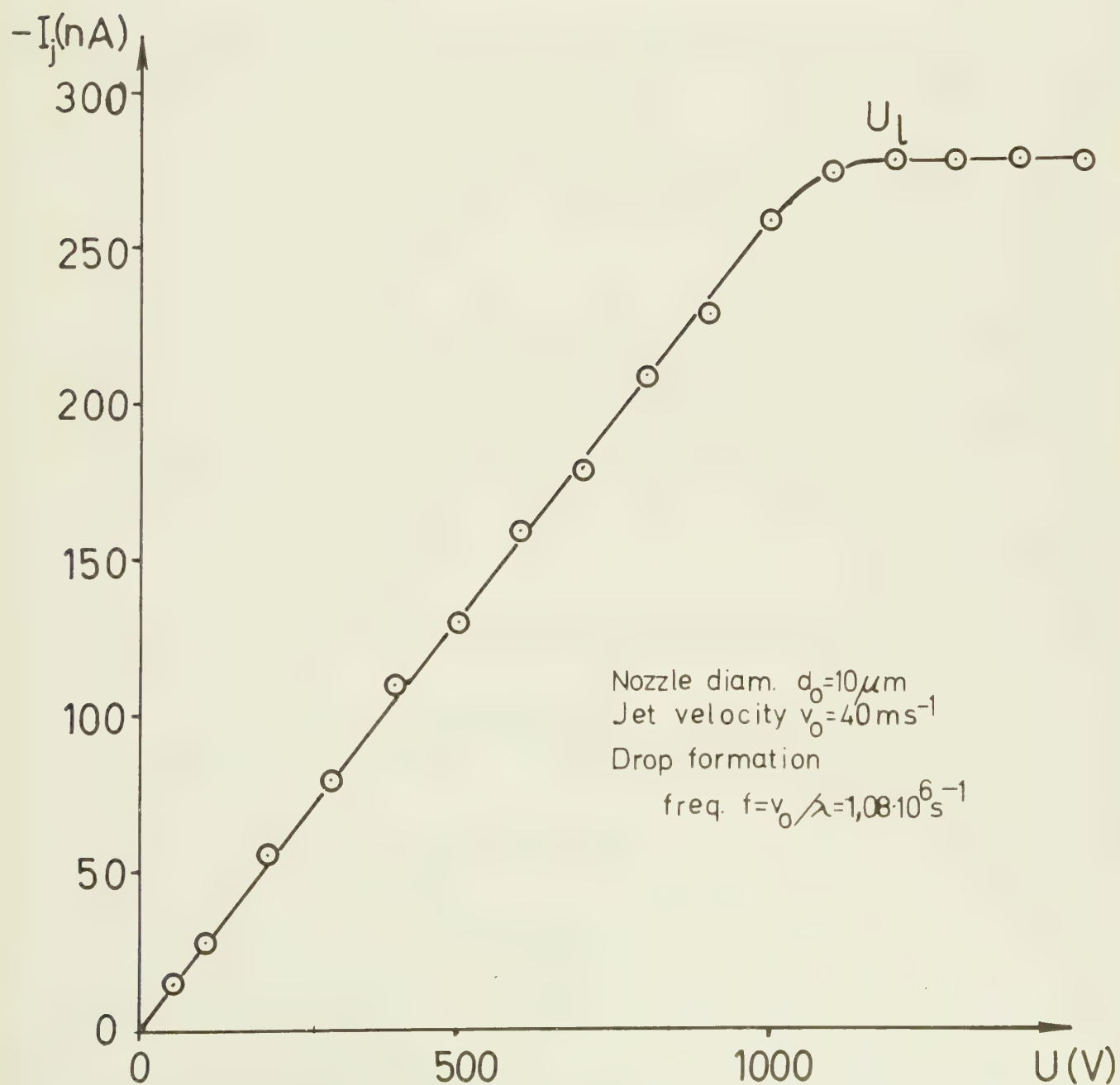


Fig. 2:8. Jet current as a function of the voltage applied to control electrode.

a corona discharge is created between the jet and the electrode. Above this voltage the jet current is unaltered. The corona discharge is situated at the point of drop formation and barely visible in darkness.

The jet current may be calculated theoretically by referring to Fig. 2:9. The total jet current I_j is the product of the number of drops formed per second n and the charge q induced on one drop.

$$I_j = n \cdot q \quad (7)$$

The charge q induced on the drop just about to be formed is

$$q = \sum_i C_i U_i \quad (8)$$

where C_1 is the capacitance and U_1 the voltage between the drop and the charging electrode and $C_2, C_3 \dots U_2, U_3 \dots$ the capacitance and voltage between the drop just being formed and the newly formed drops.

If we neglect the influence from the preceding drops the charge q will be:

$$q = C_1 U_1 \quad (8a)$$

C_1 may be approximated by considering the jet as the center conductor of a cylindrical coaxial line with the outer conductor consisting of the cylindrical inside of the charging electrode with radius r_1 . The capacitance per unit length of this line is multiplied by the length S of the jet required to form one drop to get a value for the charging capacitance:

$$C_1 = \frac{2\pi\epsilon_0 S}{\ln r_1/r_0} \quad (9)$$

where r_0 is the radius of the jet and ϵ_0 the permittivity of free space.

For a nozzle diameter of $10 \mu\text{m}$, a jet speed of 40 m/s and a drop formation frequency of $1.08 \cdot 10^6 \text{ s}^{-1}$ the following result is obtained:

$$C_1 = \frac{2\pi \cdot 10^{-11} \cdot 3.7 \cdot 10^{-5}}{\ln 1.5 \cdot 10^{-3} / 5 \cdot 10^{-6}} = 4.1 \cdot 10^{-16} \text{ F}$$

and for e.g. $U_1 = -500 \text{ volts}$

$$q = -4.1 \cdot 10^{-16} \cdot 500 = -2.0 \cdot 10^{-13} \text{ As}$$

which gives a jet current

$$I_j = n \cdot q = -1.08 \cdot 10^6 \cdot 2.0 \cdot 10^{-13} = -220 \text{ nA}$$

where n is the number of drops formed per second. This value should be

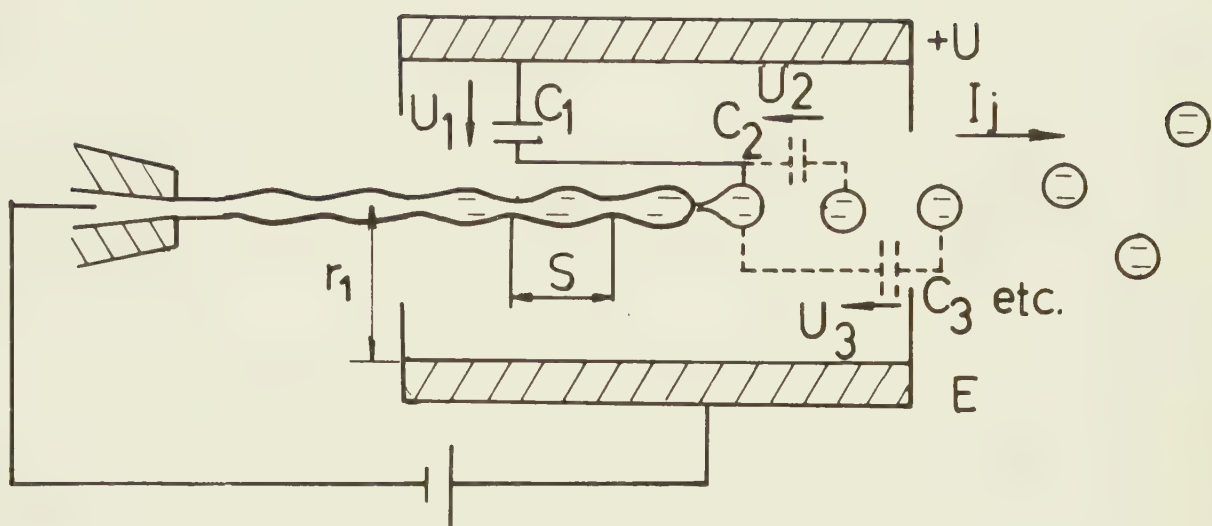


Fig. 2:9. Geometry used in calculation of jet currents.

compared with the value -130nA from Fig. 2:8. The lower experimental value is expected due to the neglecting of the influence from the newly formed and negatively charged drops, which compensate the field from the positively charged control electrode at the point of drop formation.

An estimation of the electric field E_d at the surface of the drop is of interest for finding probable reasons for the occurrence of the corona discharge. This field intensity can be found by means of Gauss' law:

$$E_d = \frac{D_d}{\epsilon_o} \approx \frac{q_1}{\epsilon_o A_d} = \frac{q_1}{\epsilon_o \pi \cdot d_d^2} \quad (10)$$

where D_d is the displacement charge, A_d the surface area of the drop and q_1 the drop charge corresponding to U_1 . Inserting the value of q_1 , which causes the corona discharge at about 1100 V as shown in Fig. 2:8 gives a value of

$$E_d = \frac{280 \cdot 10^{-9}}{10^6 \cdot 10^{-11} \cdot \pi \cdot 1.8^2 \cdot 10^{-10}} = 2.7 \cdot 10^7 \text{ V/m} = 270 \text{ kV/cm}$$

This is an extremely high value which greatly exceeds the normal breakdown values for air. However, it may be noted that the radial electric field decreases inversely proportional to the square of the distance from the center of the drop. This is in accordance with the findings of Müller (1956) who has reported that a surface field strength of about 10^5 kV/cm may be allowed before a field emission of ions from the surface will occur. Thus our value seems to be well below this limit.

A more conceivable reason for the occurrence of a corona discharge may be sought in a surface displacement which results in a higher field strength at certain points of the separating drop. Hendricks (1962) states, on the basis of Lord Rayleigh's formula, that a droplet becomes unstable against surface displacements if its charge is larger than:

$$q_{\text{limit}} = \frac{m_d \cdot 10^{-6} \cdot \sigma^{1/2}}{\rho \cdot \pi^{1/2} r_d^{3/2}} \quad (11)$$

where m_d is the mass of the drop, σ the surface tension (dynes/cm), ρ the density of the liquid and r_d the drop radius. Inserting the values for the jet in Fig. 2:8 results in:

$$q_{\text{limit}} = 4.5 \cdot 10^{-13} \text{ As}$$

The corona discharge for the jet in Fig. 2:8 occurs for a charge:

$$q_{\text{corona}} = \frac{I_{j\text{max}}}{n} = 2.6 \cdot 10^{-13} \text{ As}$$

which may indicate that the proposed mechanism is possible. Several attempts to obtain microphotographs of this phenomenon, however, have not been successful.

In the calculations given above it was assumed that the electric potential of the jet at the point of drop formation was known. Obviously this is only the case if the jet current I_j does not cause a voltage drop in the continuous part of the jet between the point of drop formation and the electrode connecting the ink in the nozzle to the minus side of the control voltage U . Therefore, the resistivity of the ink as well as the diameter and length of the continuous part of the ink extending from the nozzle to the point of drop formation is of importance, because of which this will be studied in the following.

The resistivity (ρ_e) of the liquid used in this measurement was about $4 \Omega \text{ m}$. In order to verify that the current I_j (cf. Fig. 2:7) flowing from the point of drop formation to the ground connection point does not produce a considerable voltage drop, we calculate the resistance of the continuous part of the jet protruding from the nozzle according to the formula:

$$R = \rho_e \cdot \frac{L \cdot 4}{\pi d_o^2} \quad (12)$$

where R is the resistance, L the length and d_o the average diameter of the continuous column of the jet, which gives the main contribution to the resistance between the drop formation point and ground. With $\rho_e = 4 \Omega \text{ m}$, $L = 2.3 \text{ mm}$ (Section 2.2) and $d_o = 10 \mu\text{m}$, the value of R according to (12) is

$$R = 4 \frac{2.3 \cdot 10^{-3} \cdot 4}{\pi \cdot 10^{-10}} \approx 120 \text{ M } \Omega$$

According to Fig. 8 the maximum current is

$$I_{j\text{max}} = 280 \text{ nA } (U = 1100 \text{ V})$$

The corresponding maximum voltage drop is $U_{o\text{max}}$.

$$U_{o\text{max}} = R \cdot I_{j\text{max}} = 34 \text{ V}$$

which may be neglected compared with the control voltage U of 1100 V.

Since I is proportional to U below the limiting voltage U_1 (Fig. 2:8) the ratio U_o/U is constant and U_o may be neglected throughout the range.

2.4. Influence of air resistance on drop movement

The understanding of the fundamental differences in behaviour of uncharged and charged drops during their flight through the air from the drop formation point to the recording paper is of great importance for choosing optimal conditions for the modulation process depending on the application. A presentation of results obtained in a microphotographic investigation is presented by Månsson (1972). Thus, a short summary will be given here with special attention to certain phenomena which are essential for the intensity modulation.

2.4.1. All drops uncharged

Drops which are separated from the continuous part of the jet while there is no voltage on the control electrode remain uncharged and should in principle move through the air with constant velocity one after another. However, during their flight, they are exposed to the wind resistance, which causes an irregular retardation of drops of different sizes which is shown in Fig. 2:10. Here the jet from a 10 μm nozzle with an exit velocity of 20 m/s has travelled about 10 mm through the air. A merger of some of the drops during their flight through the air has taken place which results in drops of very different size as well as great variations in the distance between the drops. This causes irregularities and interruptions in the recording trace if the ink jet is used in e.g. a facsimile apparatus.

The best way to avoid these irregularities is by the use of electro-mechanical vibrations generated by a piezoelectrical crystal as mentioned before. This reduces the differences in drop size and thus also the retarding forces due to air friction, which results in a jet with equidistant drops which is shown in Fig. 2:11, where a 10 μm jet with an exit velocity of 40 m/s, controlled by a 1.08 MHz vibration is photographed after having travelled about 10 mm through the air.

2.4.2. All drops charged

When the separation of drops from the continuous part of the jet occurs while a constant voltage is applied between the control electrode and the jet, these drops will be charged. The charged drops act upon each other

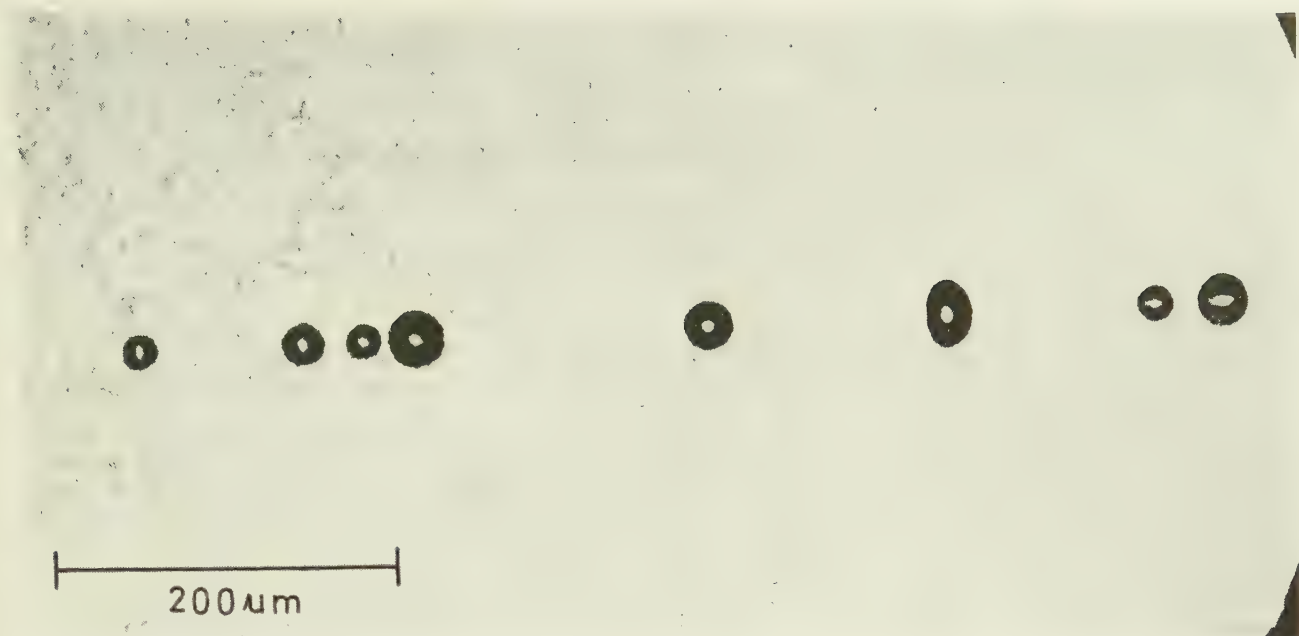


Fig. 2:10. Drops of a 10 μm jet 10 mm from nozzle when drop formation is not controlled by mechanical vibrations. Jet velocity 20 m/s.



Fig. 2:11. Drops of a 10 μm jet 10 mm from nozzle when drop formation is controlled by mechanical vibrations of a frequency of 1.08 MHz. Jet velocity 40 m/s.

with repulsive forces, a fact which has two essential consequences for the drop flight through the air:

- a) The merger of drops does not occur.
- b) The drops will be repelled out from the jet axis.

The prevention of merging is illustrated in Fig. 2:12 where a jet with the same parameters and having travelled the same distance through the air as the jet in Fig. 2:10 is shown. The only difference is that in this case a voltage of 100 V was applied to the control electrode. Since the electrostatic repulsive force between two drops is inversely proportional to the square of the distance between their centres, this is obviously an effective way to prevent the coalescence between drops mentioned above. However, the drawback with the decreasing quality of the recording trace due to repulsion of drops perpendicular to the jet axis mentioned by Månsson (1972) must be observed because of which the method cannot be used in actual recording devices.

While the repulsion between the drops perpendicular to the jet axis is a drawback in the attempt to get a perfect recording trace, it is advantageous for destroying the jet in order to remove the recording trace entirely (cf. Fig. 2:1). If the charging voltage is increased it is observed that an axial repulsion resulting in the spray formation takes place when the voltage exceeds a lower limiting voltage. This limit is about 200 V with the jet parameters given in Fig. 2:8. Above this voltage the repulsive forces are so large that they impart an increasing velocity component perpendicular to the jet axis, resulting in an increase of the top angle of the cone-formed spray. This is shown in Fig. 2:13 for three different charging voltages.

The existence of a lower limit of the charging voltage for the spray formation seems to be a consequence of the force balance between the stabilizing aerodynamic and the repulsive electrostatic forces. While the repulsive forces between the electric charges on the drops tend to destroy the linear train of drops constituting the jet, aerodynamic forces counteract this tendency. This seems to be due to the fact that a drop somewhat out of the line experiences a higher air resistance force during its flight through the air, the direction of which is such that it tends to push the drop back into its correct position in the drop train. This effect can be observed also to the left in Fig. 2:15, which shows that even the charged drops travel in good order during the first 5 mm after being charged at the point of drop formation. This is the case in spite of the fact that the action of the repulsion

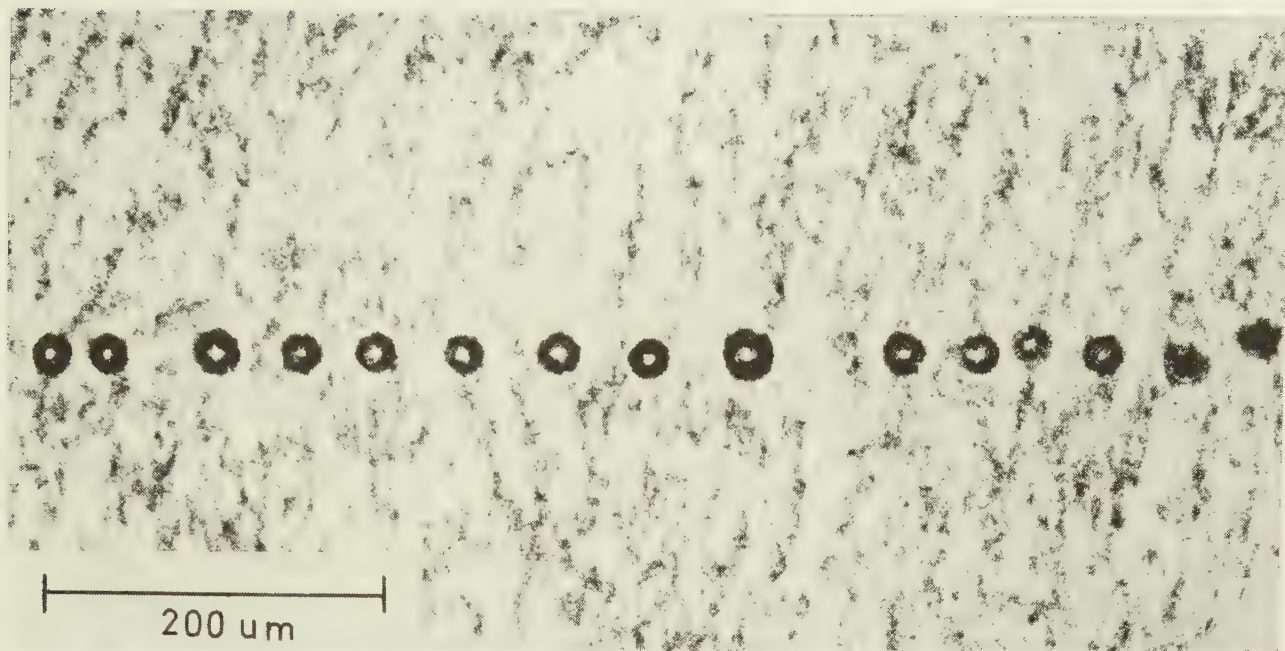


Fig. 2:12. Same as Fig. 2:10 except that drops are charged by applying 100 V to control electrode.

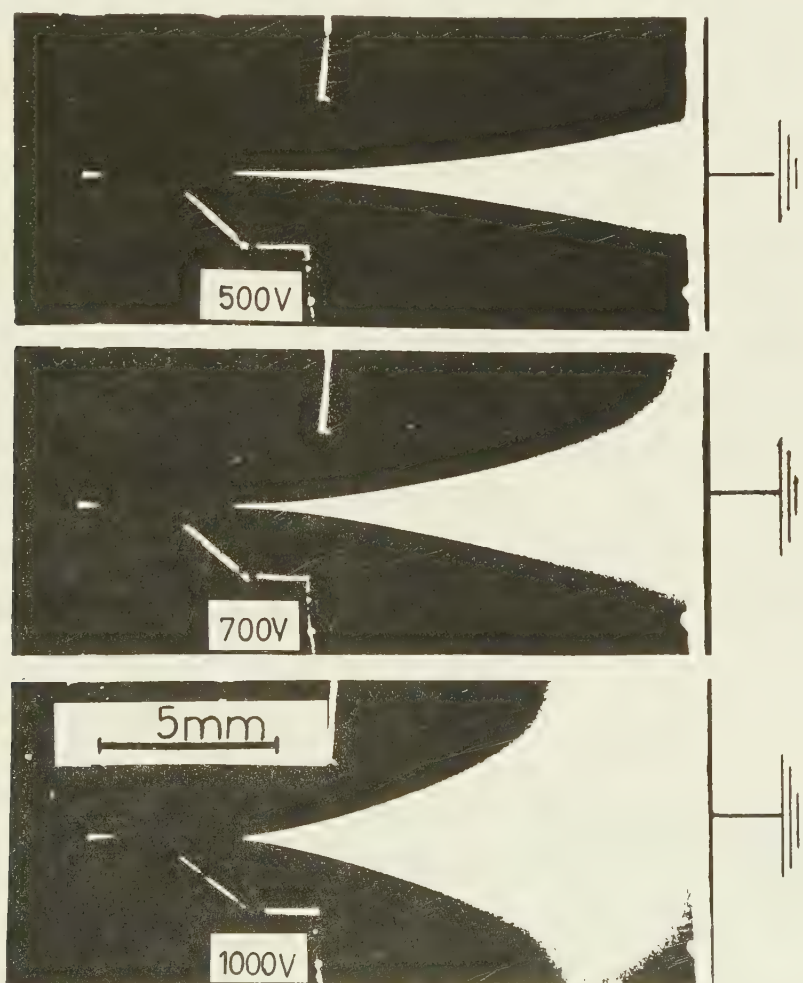


Fig. 2:13. Appearance of ink spray at three different voltages on the control electrode.

forces between the charged drops is clearly observable in Fig. 2:15. However, because of the above mentioned stabilizing influence of the air this action takes place only in the direction of the jet axis during the first 5 millimeters of jet travel. For the same reason the spray develops not directly after the point of drop formation.

In order to verify the action of air friction to some extent, the stabilizing action of the surrounding air on the train of drops will be studied theoretically in the following by estimating the drop charge necessary to break up the jet.

For the sake of the argument we assume that the center of a spherical drop D_2 has been repelled one drop radius from the central axis of the jet as shown in Fig. 2:14a. In this position the component of the aerodynamic retarding force directed towards the jet axis can be assumed to be approximately a maximum. Thus, if the drop D_2 is to be removed further from the jet axis, this stabilizing force must be exceeded by the electrostatic repulsive force.

The aerodynamic retarding force on one single drop can be estimated from the microphotograph in Fig. 2:16. (For a detailed description of Fig. 2:16 see section 2.4.3.). For an uncharged jet with an initial velocity of 40 m/s no appreciable retarding of the drops takes place during their first 10 mm flight through the air. This is also valid approximately for the uncharged drop trains of the jet in Fig. 2:16. The drops, which are pulsed out from the axis of the jet, however, undergo a retardation $\bar{R}$. From measurements on the microphotographs we find for $\bar{R}$:

$$\bar{R} \approx 6 \cdot 10^4 \text{ m/s}^2$$

Consequently, the aerodynamic retarding force $\bar{F}_d$ on the whole drop is

$$\bar{F}_d = m \cdot \bar{R} \quad (13)$$

where m = mass of the drop.

Now, the drop D_2 in Fig. 2:14a is assumed to be partly exposed to the wind resistance which results in a retarding force component $\bar{F}$:

$$\bar{F} \approx \frac{\bar{F}_d}{2} = \frac{m\bar{R}}{2} \quad (14)$$

(cf. the hatched area in Fig. 2:14b).

In order to simplify the calculation of the component directed inwards

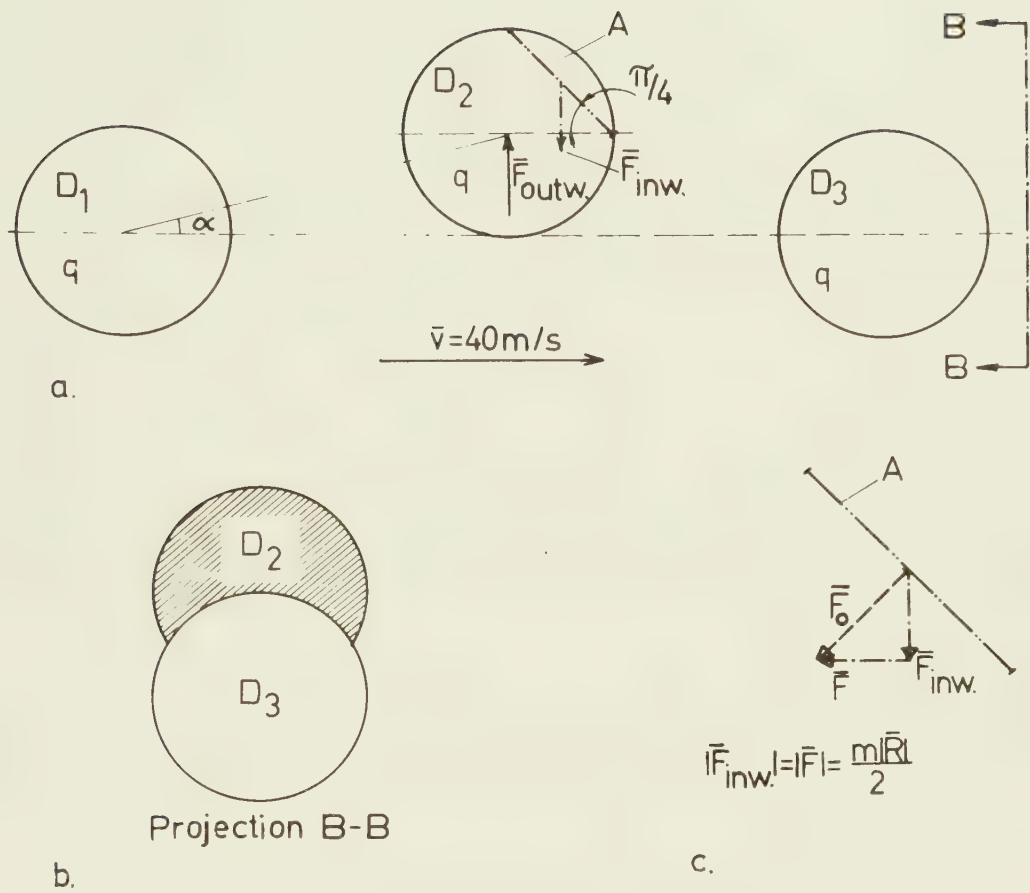


Fig. 2:14. Geometry used for calculation of air stabilizing force on drop trains.

of the total wind resistance force the following considerations were made. Under the assumption of linear air flow the part of the spherical surface of drop D_2 which is exposed to wind resistance is the hatched one in projection B-B shown in Fig. 2:14b. Now, to avoid the integration of the force component directed inwards over this complicated surface, the surface was approximated by the plane area A , elevated by an angle $\pi/4$ out of the direction of the jet axis. This area was assumed to be so large that the area of its projection perpendicular to the wind direction (Projection B-B) equals the area of the projection of the part of drop D_2 exposed to the wind resistance. Thus, the total wind force on the area A might be assumed to equal the wind force on the hatched area in 2:14b.

For the determination of the force component $\bar{F}_{inw.}$ directed towards the jet axis, the surrounding air is treated as nonviscous. Then no force can be exerted on the area A parallel with it, and the resultant $\bar{F}_O$ must be directed perpendicular to the area. Thus according to Fig. 2:14c the size of $\bar{F}_{inw.}$ is:

$$|\bar{F}_{inw.}| = 1/2 m |\bar{R}| \quad (15)$$

which can be assumed to be a reasonable approximation of the force component which tries to push the drop back into its correct position.

On the other hand, the electrostatic repulsive force on drop D_2 , which is directed outwards and primarily caused by the interactions with the nearby drops (D_1 and D_3) is given by:

$$|\bar{F}_{outw.}| = 2 \cdot \frac{1}{4 \pi \epsilon_0} \cdot \frac{q^2 \cdot \sin \alpha}{\left(\frac{s}{\cos \alpha}\right)^2} \quad (16)$$

wherein ϵ_0 is the permittivity of free space, q the charge of one drop, α the angle defined by Fig. 2:14 and finally s the distance between two drops along the jet axis.

From this we find that the balance between these forces

$$\bar{F}_{inw.} + \bar{F}_{outw.} = 0$$

requires an electric charge $q_{crit.}$ on the drop:

$$q_{crit.} = \frac{s}{\cos \alpha} \left(\frac{\pi \epsilon_0 \cdot m \cdot |\bar{R}|}{\sin \alpha} \right)^{1/2}$$

Thus when the charge of one drop exceeds the value $q_{crit.}$, the drop will be forced out from the jet axis, while if the drop charge is below $q_{crit.}$, it will

be pulled back in its original position in the drop train.

Inserting the values for a jet with parameters as in Fig. 2:8, for which the drop distance was $s = 3.7 \cdot 10^{-5} \text{ m}$, the drop mass $m = 2.9 \cdot 10^{-12} \text{ kg}$, the retardation $|\bar{R}| = 6 \cdot 10^4 \text{ m/s}^2$ and the angle $\alpha = 0.24 \text{ rad.}$, results in a value of $q_{\text{crit.}}$:

$$q_{\text{crit.}} = 1.7 \cdot 10^{-13} \text{ As}$$

The corresponding jet current $I_{\text{crit.}}$ is then given by

$$I_{\text{crit.}} = n \cdot q_{\text{crit.}} = 1.8 \cdot 10^{-7} \text{ A}$$

where n is the number of drops formed and charged per second, which in this case was $1.08 \cdot 10^6$ drops per second.

If we compare this value with the experimental results given in Fig. 2:8 we find that this current corresponds to a control electrode voltage $U_{\text{crit.}}$ of:

$$U_{\text{crit.}} \approx 700 \text{ V}$$

This value exceeds the practically observed lower limit for the spray formation at a distance of 7 mm from the control electrode of a jet with these parameters, which is about 300 V. However, keeping in mind the rough approximation used in the calculations above as well as the fact that a certain turbulence might exist in the surrounding air, the difference between theory and experiment seems reasonable. Thus, this estimation seems to support the assumption made above that the air friction experienced by the drops exerts a stabilizing action on the jet.

The exact behaviour of all drops is not interesting in connection with the use of the spray phenomenon in a recording process, because most of the drops are removed by means of the diaphragm shown in Fig. 2:1c. Therefore, no measurements of the form of the spray as a function of the control electrode voltage have been made. However, it has been noticed that a relatively sudden increase of the top angle of the cone formed spray occurs immediately above the lower limit for spray formation while the increase of this angle is more continuous for higher voltages. The consequences of this will be further discussed in connection with the discussion of the density curves obtained from grey scale studies of the ink jet intensity modulation system (cf. chapter 5).

2.4.3. Alternating charged and uncharged drops

As mentioned in the introduction, the intensity modulation process described here has a very high upper frequency limit. The fundamental reason for this is the high drop formation rate. Since theoretically every second drop could be charged the modulation process should have an upper frequency limit equal to half the drop formation frequency. However, in actual experiments only a considerably lower frequency limit was obtained. In order to investigate the reasons for this fact a series of microphotographs was made. The main results of this investigation are presented below, part of which has already been described in Månsson (1972).

Fig. 2:15 shows a microphotograph of a jet 7 mm after traversing a control electrode to which 500 V pulses having a duration of $10\ \mu\text{s}$ were applied with a repetition period of $25\ \mu\text{s}$. The drop formation was controlled by mechanical oscillations of 1.08 MHz, thus creating approximately 10^6 drops per second. In the figure the charged and the uncharged parts of the pulsed jet can be clearly discerned and it is shown that the preferred direction of the repulsion between the charged drops is in the beginning along the jet axis. This is due to the stabilizing action of the air as already discussed above.

Since 10^6 drops were formed per second at the point of drop formation, one would expect to find 10 charged drops followed by 15 uncharged drops in the pulses shown in the figure. However, counting the drops we find that of the originally 10 charged drops in each pulse only 7 remain, while the other 3 have been repelled into and coalesced with the adjacent uncharged drops. Further, compared to the theoretical length expected from the duration of the pulses applied to the control electrode a contraction of the length of the uncharged pulses is observed. This is due to air friction experienced by the uncharged drops and the axial repulsion between the charged drops. The contraction increases the farther the drops have travelled through the air and is due to the air resistance experienced by the front drop in every uncharged jet pulse. Moreover, the amount of fluid in the originally uncharged part of the jet increases compared with the theoretical value due to the merging with charged drops at the pulse edges mentioned above.

In order to determine the sign of the net charge of the larger drops at the edges of the pulses, the jet was directed through a transverse DC-field of about 8000 V/cm, as shown in Fig. 2:20b. The applied pulse voltage on

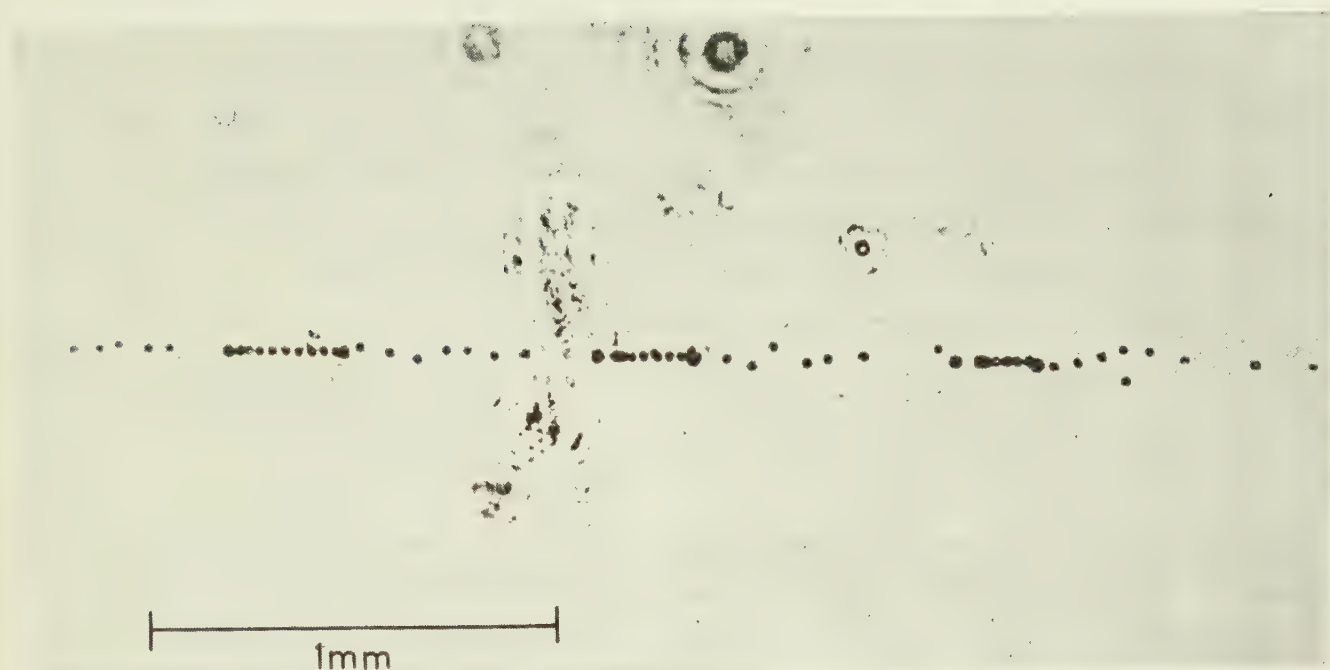


Fig. 2:15. 10 μm jet modulated by pulses 7 mm after traversing the control electrode. Pulse height 500 V, pulse length 10 μs , pulse repetition frequency 40 kHz. Repulsion can be observed between the charged drops which show a tendency to leave the jet axis. Direction of jet from left to right.

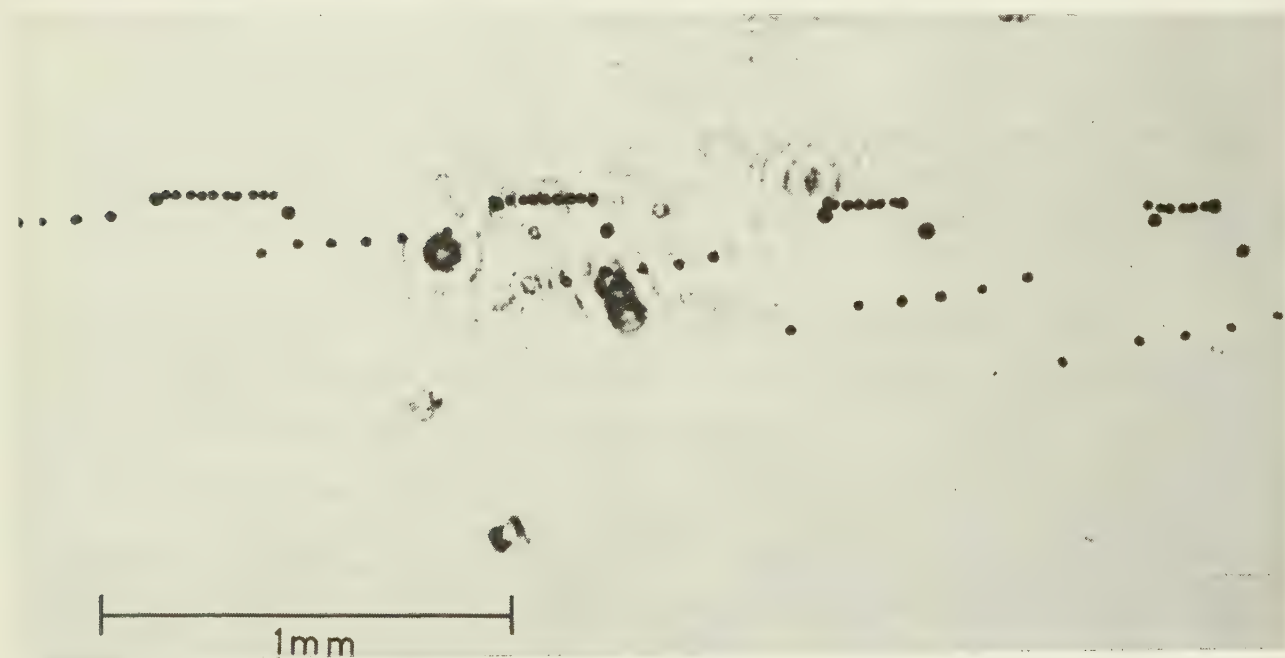


Fig. 2:16. Same as Fig. 2:15 except that a transverse DC field is applied deflecting the charged drops out of the jet axis. Pulse height in this case 300 V.

the charging electrode I was 300 V, the other parameters being the same as in Fig. 2:15. Fig. 2:16 shows the result of this experiment.

It is seen from the figure that the direction of the deflection of the large drops is the same as for the charged drops of normal size, which indicates charges of the same sign. Further, the deflection is larger for the small drops, which is expected from their higher charge to mass ratio, since every large drop is composed by both charged and uncharged drops. Fig. 2:16 shows also that drops of different size are retarded differently. According to theory the aerodynamic resistance W for a moving sphere is given by Prandtl and Tietjens (1929):

$$W = \frac{1}{2} c(\text{Re}) \cdot A \cdot \rho \cdot v^2 \quad (17)$$

where $c(\text{Re})$ is a constant depending on Reynolds' number (Re), A the projected area of the sphere perpendicular to the direction of movement, ρ the density of the surrounding medium and v the velocity of the sphere. Reynolds' number for a moving sphere is given by

$$\text{Re} = \frac{2r \cdot v \cdot \rho}{\eta} \quad (18)$$

where $2r$ is the diameter of the sphere, ρ the density and η the viscosity of the surrounding medium. Inserting the values for a normal drop from a 10 μm nozzle surrounded by air gives:

$$\text{Re} = \frac{2 \cdot 10^{-5} \cdot 40 \cdot 1.29}{0.018 \cdot 10^{-3}} = 57$$

Fig. 2:17 shows $c(\text{Re})$ according to Prandtl and Tietjens (1929). For small Re -values, $c(\text{Re})$ is inversely proportional to Re (Stoke's law), while for increasing Re it grows more independent of Re until it is constant for $\text{Re} > 1000$.

Assuming for a while that $c(\text{Re})$ is independent of Re and that no other forces than the wind resistance influence the drops in the direction of the movement, the force balance implies:

$$m \cdot \dot{v} = -k_1 \cdot r^2 \cdot v^2 \quad (19)$$

where $m = \text{const.} \cdot r^3$ is the mass of the sphere, $\dot{v} = dv/dt$, k_1 a constant, including $c(\text{Re})$, and r the radius of the spherical drops and consequently:

$$\frac{\dot{v}}{v^2} = -\frac{k_2}{r} \quad (20)$$

where again k_2 is a constant.



Fig. 2:17. For explanation see text.

This implies that the retardation of the drops is inversely proportion to their radius. Since the velocity of the different sized drops is the same at the point of entrance into the deflecting field, which causes their separation, this conclusion is qualitatively verified by Fig. 2:16.

To be more exact k_1 in equation (19) should be replaced by another $\text{const} \cdot (\text{Re})^{-\alpha}$, where α is a constant:

$$0 < \alpha < 1$$

giving the piecewise best approximation of the curve in Fig. 2:17 for the actual value of Re. This, however, only increases the tendency of larger retardation for smaller drops of the same velocity, since the relation (20) changes to:

$$\frac{\dot{v}}{v^{2-\alpha}} = \frac{k_3}{r^{1+\alpha}} \quad 0 < \alpha < 1 \quad (21)$$

where k_3 is a constant.

The difference in retardation of large and small drops should cause the merged front and final drops in a pulse to advance in relation to the other drops as shown in Fig. 2:15. This would be of importance for the use of the modulation process shown in Fig. 2:1c in an actual recording system, since a single, short train of uncharged drops might not arrive at the recording paper at the same time and thus cause two markings separated from each other. However, experiments showed a pronounced advancement for the final drop but practically none for the front drop which can also be observed in Fig. 2:15. This can be explained by the fact that the advance of the front drop is counterbalanced by a higher aerodynamic resistance, since its movement is not facilitated by preceding drops. This causes the uncharged drop trains to coalesce more and more into one single large drop on their way to the recording paper, because of which only one uninterrupted mark is obtained on the recording paper.

In certain applications it seems advantageous to use control voltages well above 1 kV. Because of this, the behaviour of a pulsed jet using high voltages on the control electrode was investigated. As mentioned, measurements of the current carried by the jet revealed that the charge on the drop is exactly proportional to the voltage on the charging electrode, up to 1100 V. Above this voltage, the drop charge was practically constant due to the fact that a corona discharge appears at the point of drop formation which keeps the field at that point essentially constant (cf. Fig. 2:8).

However, even at lower voltages the behaviour of a pulsed jet is dependent on the voltage on the control electrode. This is shown by Fig. 2:18 which is an exact duplicate of Fig. 2:15 except that the pulse voltage was 1000 V instead of 500 V, which resulted in a profound difference in the appearance of the pulsed jet. This effect can be explained as follows.

Since the drops are charged twice as much as in the 500 V case, the electrical forces between the drops are four times as great. This stronger repulsion between the drops causes a faster merging of the edge drops and thus a shortening of the pulses as observed in Fig. 2:18. However, this effect is enhanced by the fact that the large edge drops are repelling each other as shown in the right half of Fig. 2:18, which further decreases the amount of fluid in the drop train of a pulse. Because of this, drop trains generated by pulses shorter than $10\text{ }\mu\text{s}$ are hard to realize with electrode voltages exceeding 700 V, since the drop trains constituting the pulse are relatively randomly reduced in length. At higher voltages the pulses may disappear entirely. This fact has important consequences if liquid jets are used in recording devices (cf. chapter 3).

Since pulses of longer duration have a larger distance between the edge drops, the repulsion forces between them are smaller. This explains the experimental observation that the influence of pulse voltage on the reduction of the length of the drop trains is lower for longer pulses.

The effects described above make it impossible to generate pulse trains consisting of less than four or five drops. This is demonstrated by Fig. 2:19 which shows a jet 10 mm from the charging electrode, to which 500 V pulses having a duration of $22\text{ }\mu\text{s}$ have been applied to the control electrode with a repetition period of $25\text{ }\mu\text{s}$. At this distance, each drop train has merged into one large drop clearly visible in Fig. 2:19. In this case only 3 drops per period remained uncharged. Since at least 2 charged drops merge with the uncharged due to axial repulsion, the amount of liquid in the large drops generated by the merger of the original drop trains corresponds to the volume of 5 original drops, which corresponds to a pulse duration of $5\text{ }\mu\text{s}$. If the pulse length is increased above $22\text{ }\mu\text{s}$, causing less than 3 drops to remain uncharged, photographs showed that the merged drops tend to diverge from the jet axis due to their relatively large electric charge. Thus the minimum amount of liquid in each pulse cannot be less than about 5 original drops.

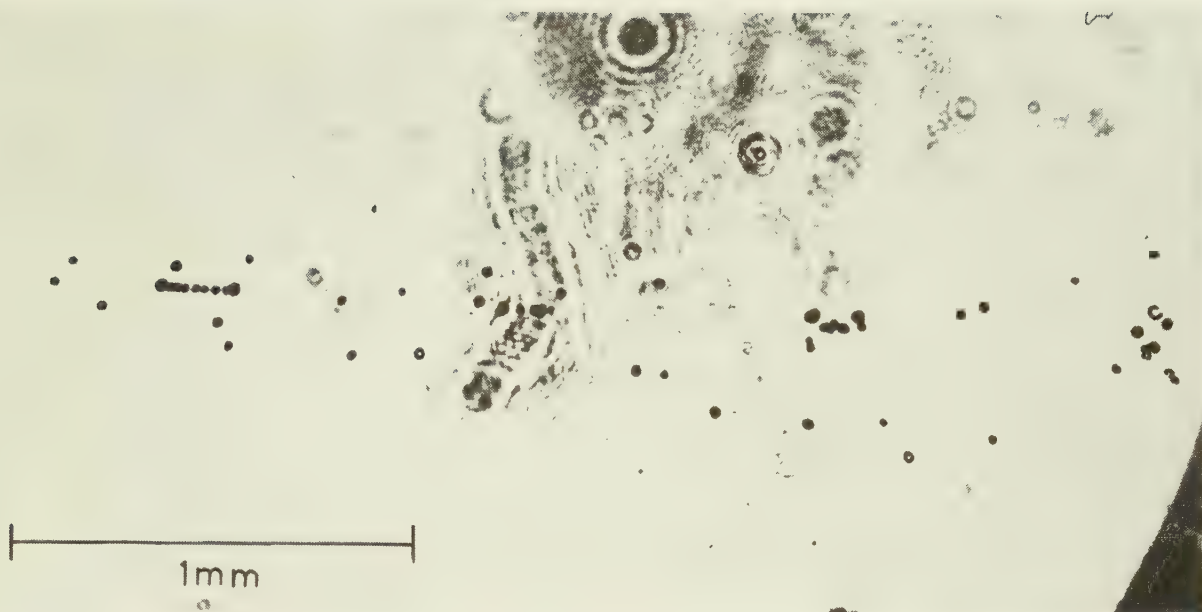


Fig. 2:18. Same as Fig. 2:15 except that pulse voltage at control electrode was increased to 1000 V.

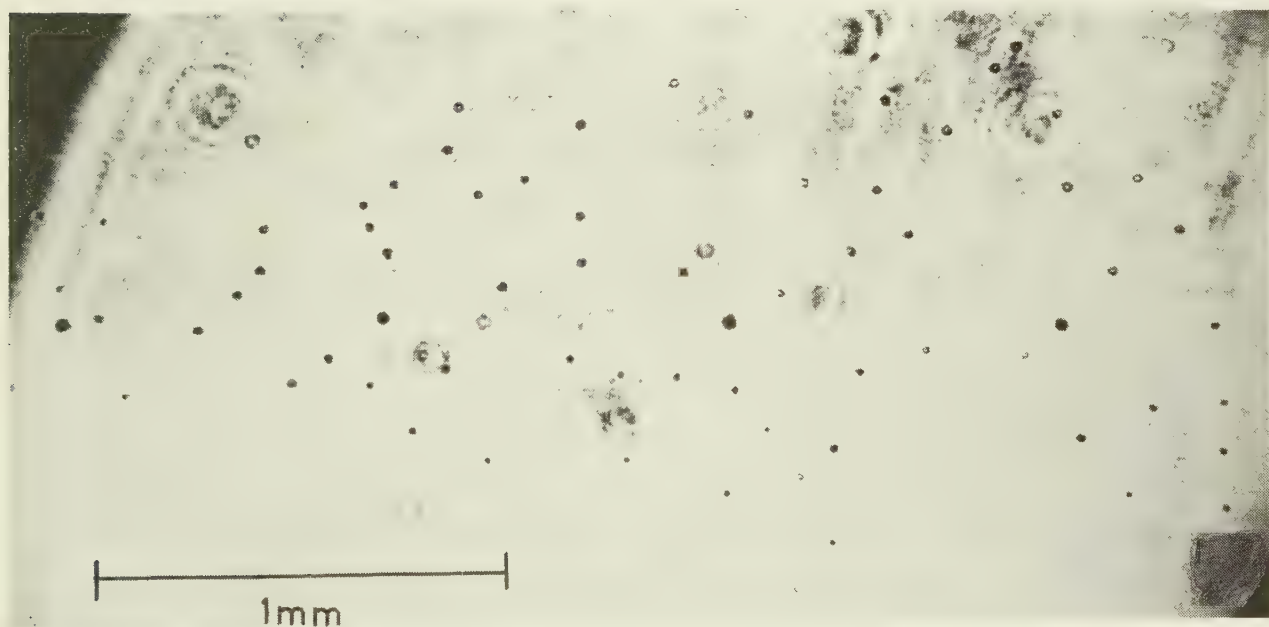


Fig. 2:19. A jet 10 mm after traversing an electrode to which 500 V pulses with a duration of 22 μ s and 40 kHz repetition frequency were applied. Direction of jet from left to right.

2.5. The removal of surplus ink

If the modulation process studied here is to be used in a recording device it is of great importance to be able to control the number of charged drops which reaches the recording paper. E.g., in an on-off recording method it is desirable to prevent all charged drops from reaching the paper, since they will give rise to a general background. Three possible ways to suppress this background by removal of the surplus drops are schematically shown in Fig. 2:20. These will be discussed in detail in the following.

2.5.1. Diaphragm method

The background can most easily be reduced appreciably by placing a diaphragm in front of the recording paper as shown in Fig. 2:20a. This diaphragm has a small aperture, the axis of which is congruent with the axis of the undisturbed jet and allows, therefore, only a small part of the spray to reach the recording paper. This is the only way to make a controllable amount of charged drops pass to the recording paper and accordingly the only way to control continuously the density of the recording trace by only varying the control electrode voltage. An obvious difficulty with this system is to keep the aperture clean, since the diameter of it must be in the order of some tenth of a millimeter to assure a reasonable definition of half tone recording. A practical solution of this problem will be discussed in section 2.7.

2.5.2. Deflection field method

Another way to decrease background can be obtained by the deflection of the charged drops in a DC electric field as shown in Fig. 2:20b while the undisturbed jet is not influenced by the field. This method allows only for the on-off modulation of the recording trace and shows certain other disadvantages. For the better understanding of the properties of this method for background reduction it will be studied in more detail in the following.

The electrostatic force F_t on a drop carrying a charge q in a transversal electric field E is given by:

$$F_t = qE \quad (22)$$

This force imparts to a drop with mass m an acceleration of:

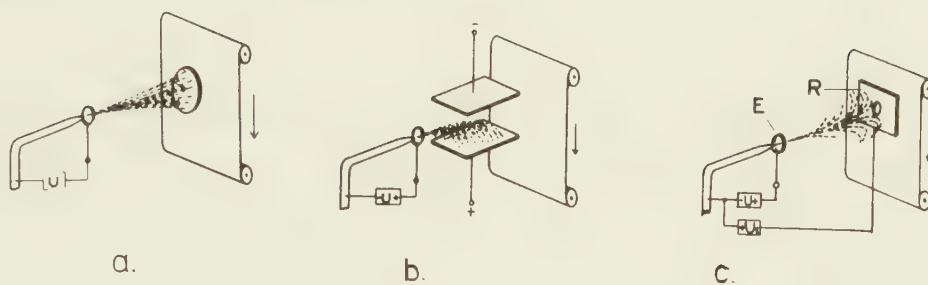


Fig. 2:20. Methods to prevent the charged drops of the ink spray to reach the recording paper. a. Intercepting diaphragm. b. DC deflection field. c. Retarding electric field.

$$\alpha = \frac{qE}{m} \quad (23)$$

resulting in a total deflection of the drop

$$y = \frac{1}{2} \cdot \frac{qE}{m} \cdot t^2 \quad (24)$$

where t is the transit time in the transversal field.

In the following calculation we assume that no retarding of the drops by air friction takes place. Then we have

$$t = \frac{l}{v_o} \quad (25)$$

where l is the length of the transversal field and v_o the entrance velocity of the jet along the jet axis. From (24) and (25) then follows

$$y = \frac{1}{2} \cdot \frac{qE}{m} \cdot \frac{l^2}{v_o^2}$$

Inserting the jet parameters given in Fig. 2:8, i.e. $q(500V) = 1.2 \cdot 10^{-13} As$, $m = 2.9 \cdot 10^{-12} kg$, $v_o = 40 m/s$ and assuming $l = 2 \cdot 10^{-2} m$ and $E = 8 \cdot 10^5 V/m$ we find:

$$y = \frac{1}{2} \cdot \frac{1.2 \cdot 10^{-13} \cdot 8 \cdot 10^5 \cdot 4 \cdot 10^{-4}}{2.9 \cdot 10^{-12} \cdot 4^2 \cdot 10^2} = 4 \cdot 10^{-3} m = 4 mm$$

Thus the transversal field seems to be a powerful means to extract the charged drops from the uncharged. The merged edge drops, however, cause difficulties, since they also have a certain charge. However, their charge to mass ratio is lower and consequently they will be deflected less which was already mentioned in section 2.4.3. and shown in Fig. 2:16. Especially when recording small dots (short ink drop trains) it is attractive to let these large drops pass to the recording paper, since they contain a large amount of ink compared with the total amount constituting the dot. Thus these large edge drops will contribute appreciably to the density of the dot. This demand of extracting the normal sized charged drops effectively from the uncharged with a transversal field, while the merged drops should not be affected at all, is difficult to fulfill. In spite of that the method has been used to remove the background in the intensity modulated galvanometer system described by Hertz and Simonsson (1969). In this case the velocity of the recording paper is relatively low because of which a slight deflection of the large drops on their way to the recording paper does not decrease the quality of the recording trace appreciably. However, as soon as the speed of the recording paper is increased above about 5 cm/s, the deflected edge drops can clearly be observed. This is shown in Fig. 2:21a, which shows

magnified modulated recording traces which were turned "on" with a 30 μ s pulse. In this experiment the recording paper was mounted onto a rotating drum as described by Hertz and Månsson (1972). The surface velocity of the drum was about 5 meters per second. The other parameters are given in the following:

Ink jet diameter	10 μ m
Ink jet velocity	40 m/s
Distance from nozzle to recording paper	$2.1 \cdot 10^{-2}$ m
Length of deflecting field	ca. $8 \cdot 10^{-3}$ m
Field strength of deflecting field	$4 \cdot 10^5$ V/m

In Fig. 2:21a a small dot can clearly be observed after each pulse recorded on the paper. This dot is caused by the trailing edge drop at the end of the drop train causing the main pulse marking on the paper. The large drop preceding the drop train cannot be observed here since it falls onto the main pulse recorded on the paper. However, using a vibrating capillary system as described by Ernbo (1972) or Hertz and Månsson (1972) and paper speeds of 25 cm or more even the preceding drop can be detected easily.

These large, slightly charged drops at both ends of a train of uncharged drops seriously impair the usefulness of the transverse field method for background reduction as shown in Fig. 2:20b. This is clearly demonstrated by Fig. 2:21b, which shows an enlarged picture of alphanumeric characters which were generated by a computer on a drum recorder with an ink jet. All parameters were the same as those shown in Fig. 2:21a. For the same reason the transverse field method is difficult to use with ink jet printing of alphanumeric characters as described by Ernbo (1972) and Hertz and Månsson (1972). Thus, in spite of the fact **that** the transverse field method is very efficient in reducing the background generated by the ink spray on the recording paper, it can be applied only in very special cases.

Besides the disadvantage described above the transverse field method may lead to other complications which decrease the reliability of the method. Because of the relatively complicated electrode system necessary to create the transverse field in the small space between the control electrode and the recording paper, stray ink drops may find their way out of the electrode system and settle on different parts of the recording apparatus, for example the insulators supporting the electrode system. Since rather high voltages are necessary to generate the high transverse field strength necessary, breakdown may easily occur along the surface of these insulators. Since

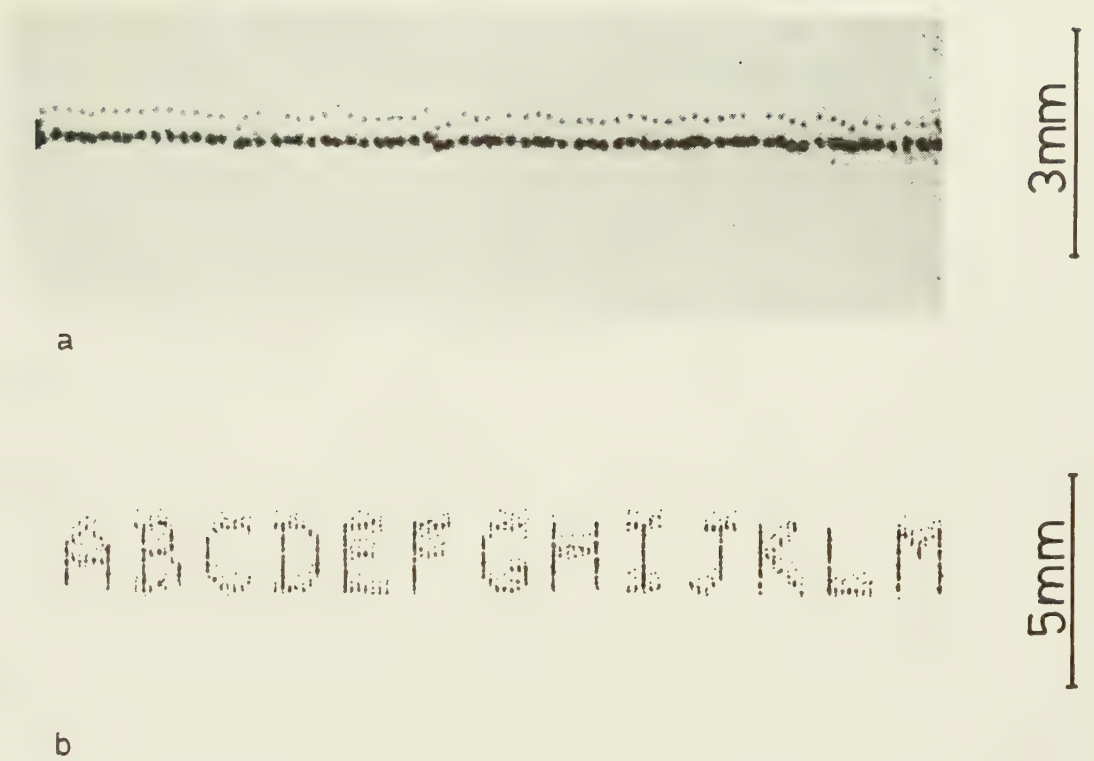


Fig. 2:21. Effect of large edge drops slightly displaced by a transversal DC field. a. Drops can be observed above main line recorded on drum recorder. b. Decrease of quality of characters recorded on drum recorder. Scanning direction vertical in both cases. (Recordings kindly provided by B. Smeds)

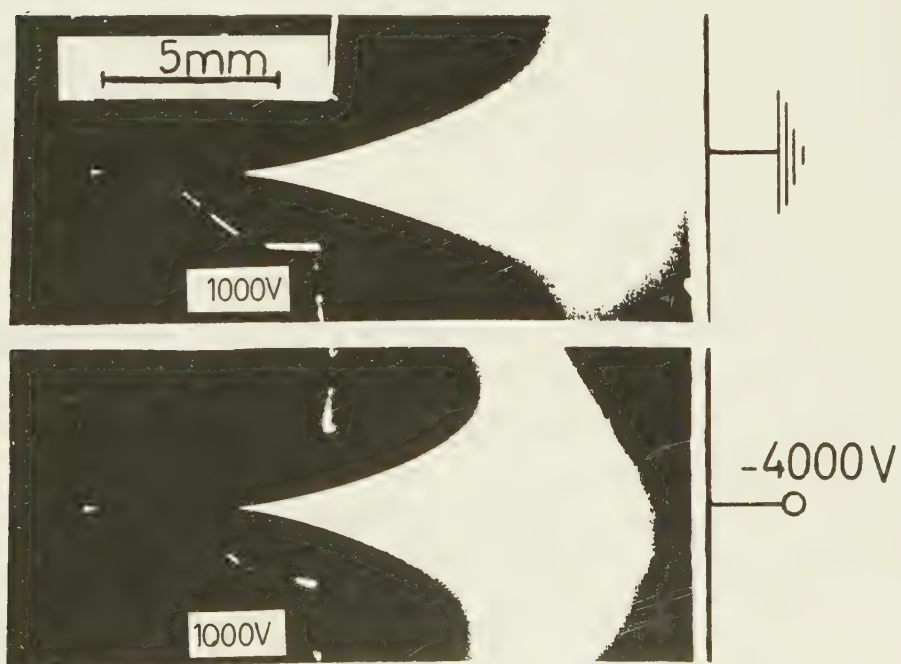


Fig. 2:22. Effect of retarding field on ink spray.

it is practically impossible to prevent stray drops from leaving the relatively open electrode system, the long-time reliability of this method might be diminished. Since these difficulties are not encountered in the electrode system based on the diaphragm method described by Månsson and Hertz (1972) the latter system is preferred in most applications.

2.5.3. Retarding field method

In the previous paragraph the charged drops of the spray were prevented from reaching the recording paper by a transverse electric field which deflected the drops perpendicular to the axis of the jet. However, since the drops of the spray are charged, it is also possible to stop their flight in the direction of the recording paper by an electric retarding field established between the control electrode and the recording surface. The direction of this field should be chosen in such a way that its lines of force are essentially parallel to the jet axis and its polarity such, that the velocity of the charged drops is decreased on their way to the recording surface.

An arrangement suitable for the retardation of the spray drops is shown in Fig. 2:20c. Here a retarding electrode R is placed in front of the recording paper and connected to a voltage U_1 in such a way, that the spray drops are slowed down to a stop, whereafter they return to the control electrode E due to the action of the electric field between the control electrode and the electrode R. On the other hand, the uncharged drops of the undisturbed jet can easily reach the aperture in the electrode R and travel through it to the recording paper.

This method can be modified in several ways. First of all, one can omit the retarding voltage source U_1 altogether, if the retarding electrode R is properly insulated. In that case the first drops of the spray that reach the retarding electrode R will charge this electrode until it has reached such a potential that none of the following drops will be able to overcome the opposing field and reach the retarding electrode. In this way the retarding electrode R will always be kept at a potential just sufficient to repel all the charged drops in the spray.

Further, it is possible to omit the retarding electrode R altogether and generate the retarding field by applying a suitable voltage U_1 to a metallic support of the recording paper just opposite to the control electrode E, e.g.

the drum in Fig. 2:25. Since the electric field is very little disturbed by the presence of the recording paper covering this metallic support, the effectiveness of this arrangement is practically the same as that shown in Fig. 2:20c.

In all the methods described above it is important to ensure that the retarding field cannot reach through the control electrode E and modify the electric field at the point of drop formation. If this is the case, the charge on the drops cannot be controlled properly by the control voltage only. The interference of the retarding field can be effectively prevented by a suitable form of the control electrode. This can be realized by making the control electrode in the form of a reasonably long metallic tube.

In Fig. 2:20c a voltage U_1 has been used to generate the retarding field. Obviously, the magnitude of this voltage U_1 has to be chosen in such a way that the maximum electric work $q \cdot U_1$ performed by the drops carrying an electric charge q in addition to the work performed by the air resistance is larger than or equal to their kinetic energy $E_{kin.} = \frac{1}{2}mv_o^2$, where m is the mass of a drop and v_o its velocity. To obtain an estimation of the retarding voltage necessary for the effective retardation of the drops the kinetic energy of a water drop having a diameter of $20 \mu m$ is given for different velocities v_o in Table 2.2 while Table 2.3 gives the electric work $q \cdot U_1$ for different charges q and voltages U_1 . From these tables it is seen that the electric voltage U_1 necessary to prevent the drops from reaching the recording paper is of the magnitude 2 to 10 kV depending on the charge and velocity of the drops if the influence from the air resistance is neglected.

v_o	50	40	30	20	10	m/s
$E_{kin.}$	$5.25 \cdot 10^{-9}$	$3.36 \cdot 10^{-9}$	$1.9 \cdot 10^{-9}$	$8.4 \cdot 10^{-10}$	$2.1 \cdot 10^{-10}$	Ws

Table 2.2. Kinetic energy $E = \frac{1}{2}mv_o^2$ of water drops having a diameter of $20 \mu m$ as a function of their velocity v_o .

q	U_1	10	100	1000	2000	5000	10000	V
$5 \cdot 10^{-13} \text{ As}$		$5 \cdot 10^{-12}$	$5 \cdot 10^{-11}$	$5 \cdot 10^{-10}$	10^{-9}	$2.5 \cdot 10^{-9}$	$5 \cdot 10^{-9}$	Ws
10^{-13} As		10^{-12}	10^{-11}	10^{-10}	$2 \cdot 10^{-10}$	$5 \cdot 10^{-10}$	10^{-9}	Ws
$5 \cdot 10^{-14} \text{ As}$		$5 \cdot 10^{-13}$	$5 \cdot 10^{-12}$	$5 \cdot 10^{-11}$	10^{-10}	$2.5 \cdot 10^{-10}$	$5 \cdot 10^{-10}$	Ws
10^{-14} As		10^{-13}	10^{-12}	10^{-11}	$2 \cdot 10^{-11}$	$5 \cdot 10^{-11}$	10^{-10}	Ws

Table 2.3. Electric energy $q \cdot U_1$ of water drops carrying a charge q as a function of the potential difference U_1 .

In Fig. 2:22 the effect of the retarding field on the ink jet is shown. The two photographs show a $10 \mu\text{m}$ jet with an exit velocity of 40 m/s and a control electrode voltage of 1000 V . In the upper photograph the retarding electrode R is grounded while in the lower it is connected to a voltage of -4000 V . Thus the negatively charged drops have to pass a retarding voltage of 4000 V in addition to the air resistance in the lower photograph, before they can reach the retarding electrode R. It can be seen that the drops do not manage this and are stopped and repelled backwards.

An estimation of the various kinds of energy involved in the drop flight in this case may be made. From Table 2.2. we have for drops with a velocity of 40 m/s the kinetic energy:

$$E_{\text{kin.}} = 3.36 \cdot 10^{-9} \text{ Ws}$$

The electric energy required to pass the potential difference of 4000 V for drops which a charge of $2.5 \cdot 10^{-13} \text{ As}$ is taken from Table 2.3. by interpolation:

$$E_{\text{el}} = q \cdot U_1 = 1.00 \cdot 10^{-9} \text{ Ws}$$

The energy required to overcome the air resistance E_r may be estimated by utilizing the value of the retarding force $\bar{F}_d$ given in section 2.4.2. Then if we assume that this retarding force is constant:

$$E_r = \int_0^l \bar{F}_d \cdot d\bar{s} = m_d \cdot |\bar{R}| \cdot l = 2.5 \cdot 10^{-10} \cdot 1 \text{ Ws}$$

where l (in mm) is the distance from the nozzle to the point where the drops come to rest, m_d the mass of a drop with a diameter of $20 \mu\text{m}$ and $\bar{R}$ the re-

tardation.

Since all the kinetic energy has been transformed into friction energy and electric energy before the drops stop, the distance l will be given by the equation:

$$E_{\text{kin}} = E_{\text{el}} + E_r \quad (26)$$

which gives a value of

$$l = 9.5 \text{ mm}$$

From the length scale in Fig. 2:22 we have

$$l = 16 \text{ mm}$$

The difference might be explained by the approximation of the retarding force. This force decreases with velocity and thus the drops in practice will reach longer than predicted by the equation (26) and the assumptions made above.

2.6. Ink and ink supply

The ink which has been used for the experiments is a glycerin-water solution to which is added a suitable soluble dyestuff. The requirement of solubility is important since the very fine nozzles will clog if the ink is not very carefully filtered before reaching the nozzle. This means that fine filters with relatively low capacity must be used, which in its turn will be clogged by relatively few particles. The technical properties of the ink are listed below:

Density	(ρ)	$= 1.05 \cdot 10^3 \text{ kg/m}^3$
Surface tension	(σ)	$= 73 \cdot 10^{-3} \text{ N/m}$
Viscosity	(η)	$= 2.2 \cdot 10^{-3} \text{ Ns/m}^2$
Resistivity	(ρ_e)	$= 4.0 \Omega\text{m}$

All the experiments discussed in this report have been made with ink jets generated by supplying ink under high pressure to a nozzle with a circular cross section. This pressure must overcome the pressure losses in the nozzle and tubings due to the internal friction. Further, it must provide the surface energy and the kinetic energy of the jet. Thus, we can write for the total work $\int_0^V P_O \cdot dV$ carried out per second by the pump pressure P_O , thereby producing a volume V of solid jet:

$$\begin{aligned} \int_0^V P_O dV = & \text{friction losses in the nozzle } ([P_1 + P_2] \cdot dV) \\ & + \text{generation of jet surface energy } (P_3 \cdot dV) \\ & + \text{generation of kinetic energy of the jet } (P_4 \cdot dV) \end{aligned}$$

From this we find the expression

$$P_o = \sum_i 32 \eta d_o^2 v_o \int_{l_{1i}}^{l_{2i}} \frac{dl}{d_i^4(l)} + \frac{2\sigma}{d_o} + \frac{\rho \cdot v_o^2}{2} \quad (27)$$

where P_o is the total pump pressure in the conduit leading to the nozzle, η the viscosity of the ink, l_{1i} and l_{2i} are the length limits and $d_i(l)$ the internal diameter of the capillary section i , σ the surface tension, ρ the density of the ink, d_o the diameter and v_o the mean exit velocity of the jet. The first term is a consequence of the law of Hagen-Poiseuille for laminar flow, which is valid for $Re < 2000$. The second term is the internal pressure generated inside the free jet by the surface tension from the single curved jet surface. Finally, the third term is the pressure required for the generation of kinetic energy of the jet and is evaluated from Bernoulli's law for a horizontal non-viscous liquid flow.

A sectional view of a $10 \mu m$ capillary used in most of the described experiments is given in Fig. 2:23 which also includes the typical parameter values. The calculated pressure drops for the various sections are:

$$\begin{aligned} p_1 &= 6.6 \text{ kp/cm}^2 \quad (d_1 = 60 \mu m, l_1 = 30 \text{ mm}) \\ p_2 &= 18.2 \text{ "} \quad (d_2 = 60 - 5 \cdot 10^{-2} l / \mu m, l_2 = 1 \text{ mm}) \\ p_3 &= 0 \text{ "} \quad (\text{due to surface tension}) \\ p_4 &= 8.0 \text{ "} \quad (\text{transformed into kinetic energy}) \end{aligned}$$

$$P_o = \sum p_i = 32.8 \text{ kp/cm}^2$$

which is illustrated in the pressure drop diagram in the same figure. The total pressure P_o required to maintain a velocity of 40 m/s for a $10 \mu m$ jet has been empirically found to be about 30 kp/cm^2 , which indicates that the calculated distribution is approximately correct. However, it should be observed that the result of the calculation is extremely sensitive to variations in the assumption of the shape of the capillary in the vicinity of the nozzle, because of the term d_i^4 in the denominator of the first term of eq. (27).

It may be pointed out that a lower pressure limit exists for creating a liquid jet at the end of the nozzle. This is due to the fact that the kinetic energy per unit time of the liquid flow in the capillary must be greater than the amount of energy per unit time required to create the jet surface. Thus, assuming that no contraction of the jet takes place we can write

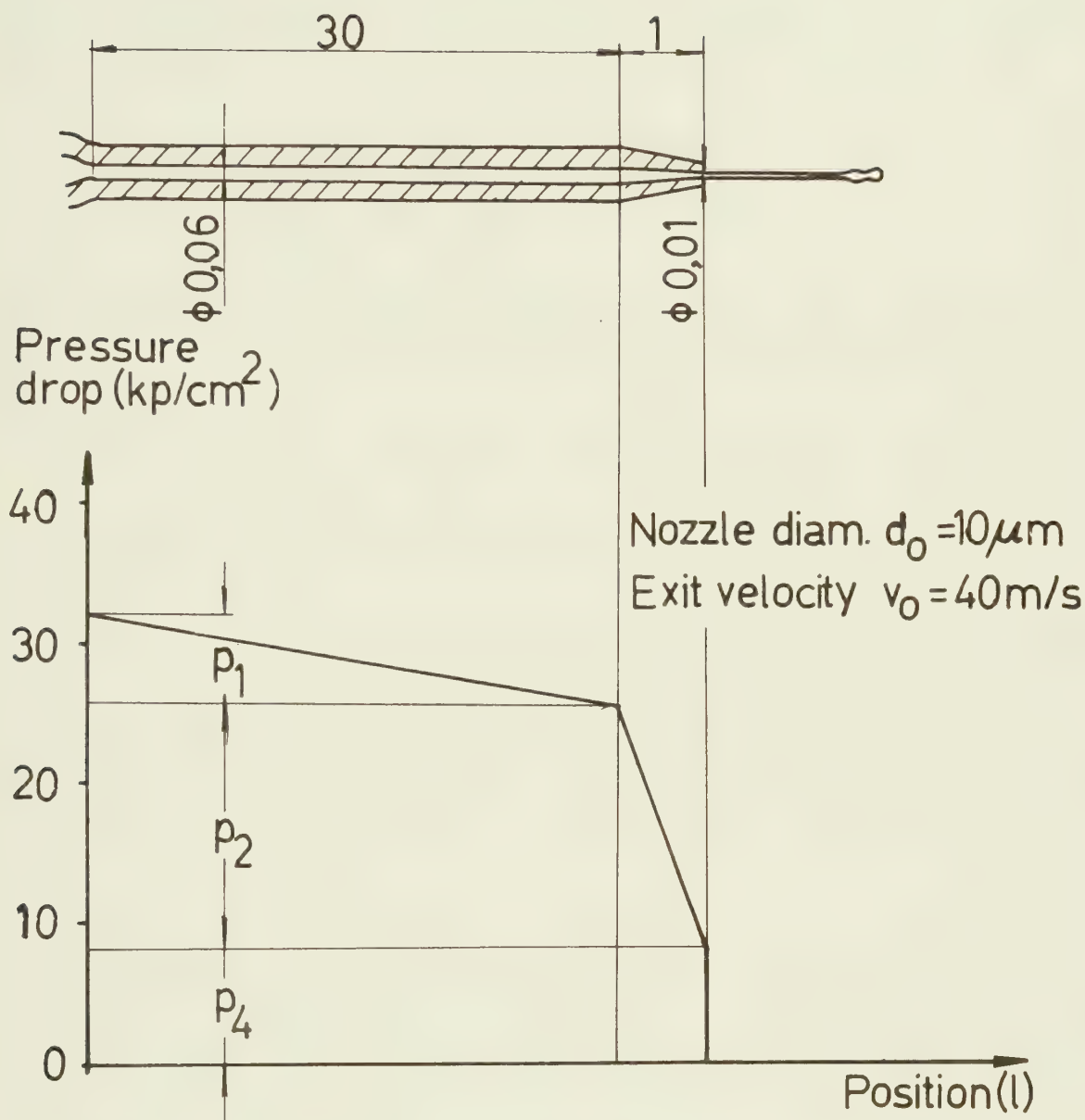


Fig. 2:23. Shape of glass capillary used for the generation of the jet investigated in this report is shown above (all measures in millimeter). The pressure drop in the different parts of the capillary is plotted below.

$$\frac{1}{2} m v_o^2 > \pi d_o v_o \cdot \sigma \quad (28)$$

with

$$m = \frac{\pi \cdot d_o^2}{4} \cdot v_o \cdot \rho \quad (29)$$

being the mass of the liquid ejected from the nozzle per second. Solving this inequality we obtain the minimum velocity required to form the jet:

$$v_{o_{\min}} = 2 \left(\frac{2 \sigma}{d_o \cdot \rho} \right)^{1/2} \quad (30)$$

Inserting the values for a 10 μm jet gives a value of:

$$v_{o_{\min}} = 7.6 \text{ m/s}$$

Neglecting the two last terms in equation (27) and observing the proportionality to v_o of the first term gives the pressure value required to maintain the velocity:

$$p_{o_{\min}} = \frac{7.6}{40} (6.6 + 18.2) = 4.7 \text{ kp/cm}^2$$

The experimental verification gave a value of $\approx 5 \text{ kp/cm}^2$.

To test the theoretical results presented above the amount of ink ejected from a 10 μm nozzle per second under various pressures has been weighed. The result is represented in Fig. 2:24. The calculated ink jet velocities shown are based on the assumption that no contraction of the jet takes place. For comparison the theoretical values based on formula (27) are also presented.

In order to try to avoid the use of the glass capillaries requiring a high pressure which mainly is lost by internal friction in the long and narrow parts of the capillaries, some experiments with small holes in metal plates used as nozzles have been carried out. The only commercially obtainable orifices with diameters small enough for the present purpose were electron microscope apertures, made of platinum with a channel of a length of 30 μm and diameters of 10, 15 and 20 μm . For such a nozzle having an internal diameter of 10 μm the first term in eq. (27) reduces to:

$$p_1 = 32 \eta v_o \cdot \frac{1}{d_o} = 32 \cdot 2.2 \cdot 10^{-3} \cdot 40 \cdot \frac{3 \cdot 10^{-5}}{10^{-10}} \approx 8.5 \text{ kp/cm}^2$$

where p_1 is the pressure drop in the nozzle for a jet with a velocity of 40 m/s which value should be compared with the sum of p_1 and p_2 which is 24.8 kp/cm^2 for a 10 μm glass capillary.

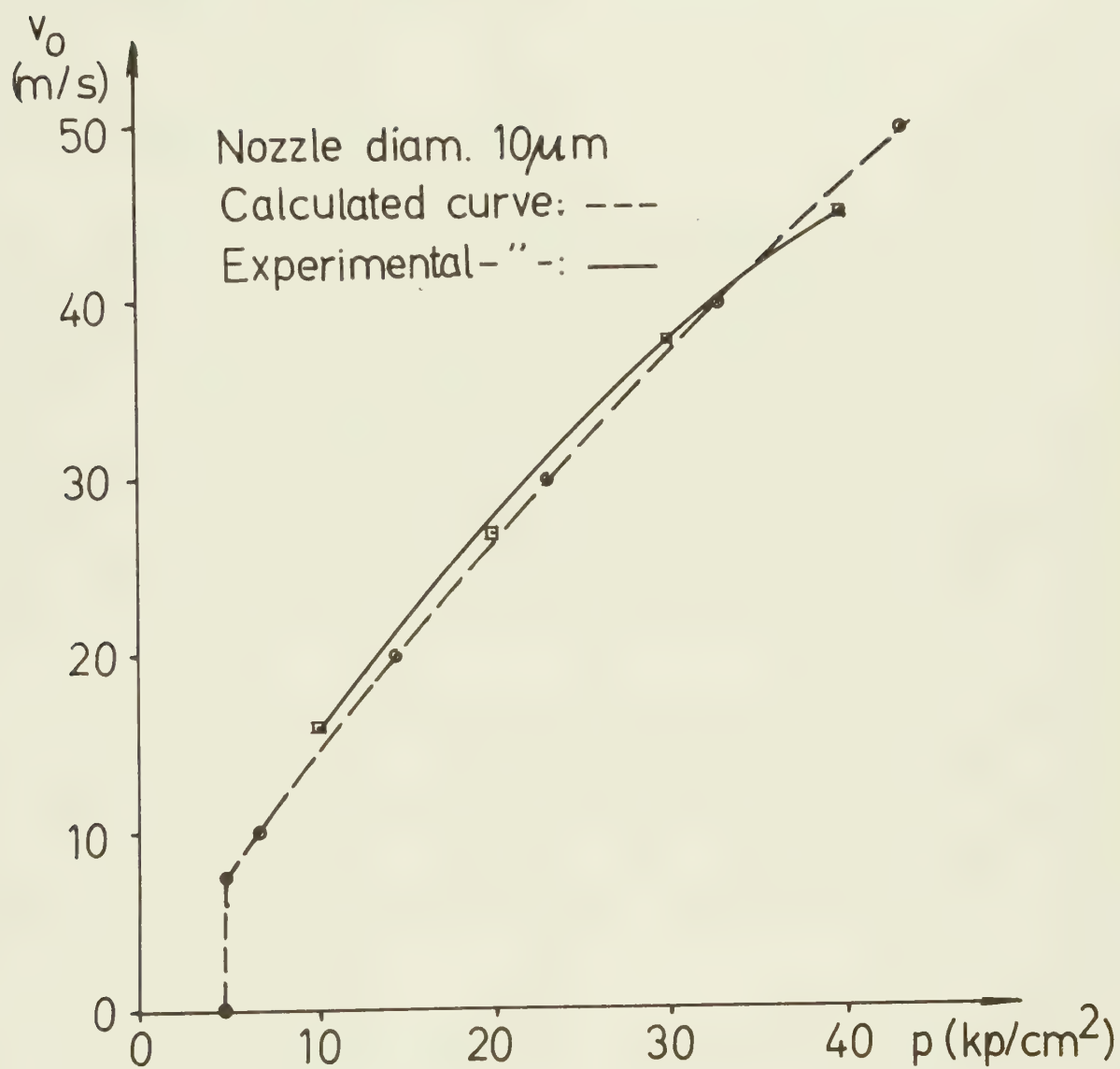


Fig. 2:24. Jet velocity as a function of ink pressure.

These nozzles functioned well and gave as well shaped jets as the glass capillaries during a relatively short time (some hours continuous ejection) whereafter the jet diameter was found to increase. An inspection of the nozzle showed a deformation of the hole which was due to the fact that the weak platinum walls cannot withstand the wear from the ejected liquid during longer periods.

2.7. Final arrangement of the ink jet device

For the intensity modulation experiments described in this report the arrangement of the capillary and the control electrode for the jet shown in Fig. 2:25 has been used. The glass capillary which leads up to the nozzle N is glued to the piezoelectric crystal C. This unit produces the fine jet of equal sized drops shown in Fig. 2:6. The charging of these drops is effected by means of the control electrode E, which also intercepts the part of the spray to be prevented from reaching the recording paper and thus combines the function of the electrode and the aperture in Fig. 2:1c. A more detailed description of the electrical properties desirable for this type of control electrode is given in Hertz and Månsson (1972).

The glass capillaries which are used in the following experiments have a profile which is shown in Fig. 2:23. They have a filter applied to their entrance end which prevents particles from reaching and clogging the nozzle. The ink is supplied to the glass capillary via plastic tubings, which must withstand the relatively high pressure needed to maintain a suitable exit velocity of the ink jet as exemplified in section 2.6.

Capillaries with filter and tubings with suitable dimensions and connections have been delivered by the Elema-Schönander Company, Stockholm.

The piezoelectric crystal C, which should vibrate in the thickness mode is tightly fixed to the heavy backing H. This backing facilitates vibrations in the desired mode. A hole of a diameter of 1 mm is drilled through the center of the crystal and the capillary is fastened to the crystal by a suitable glue. Since the difficulties of determining the energy transferred from the crystal to the jet have been discussed earlier in connection with the drop formation control nothing more will be said here.

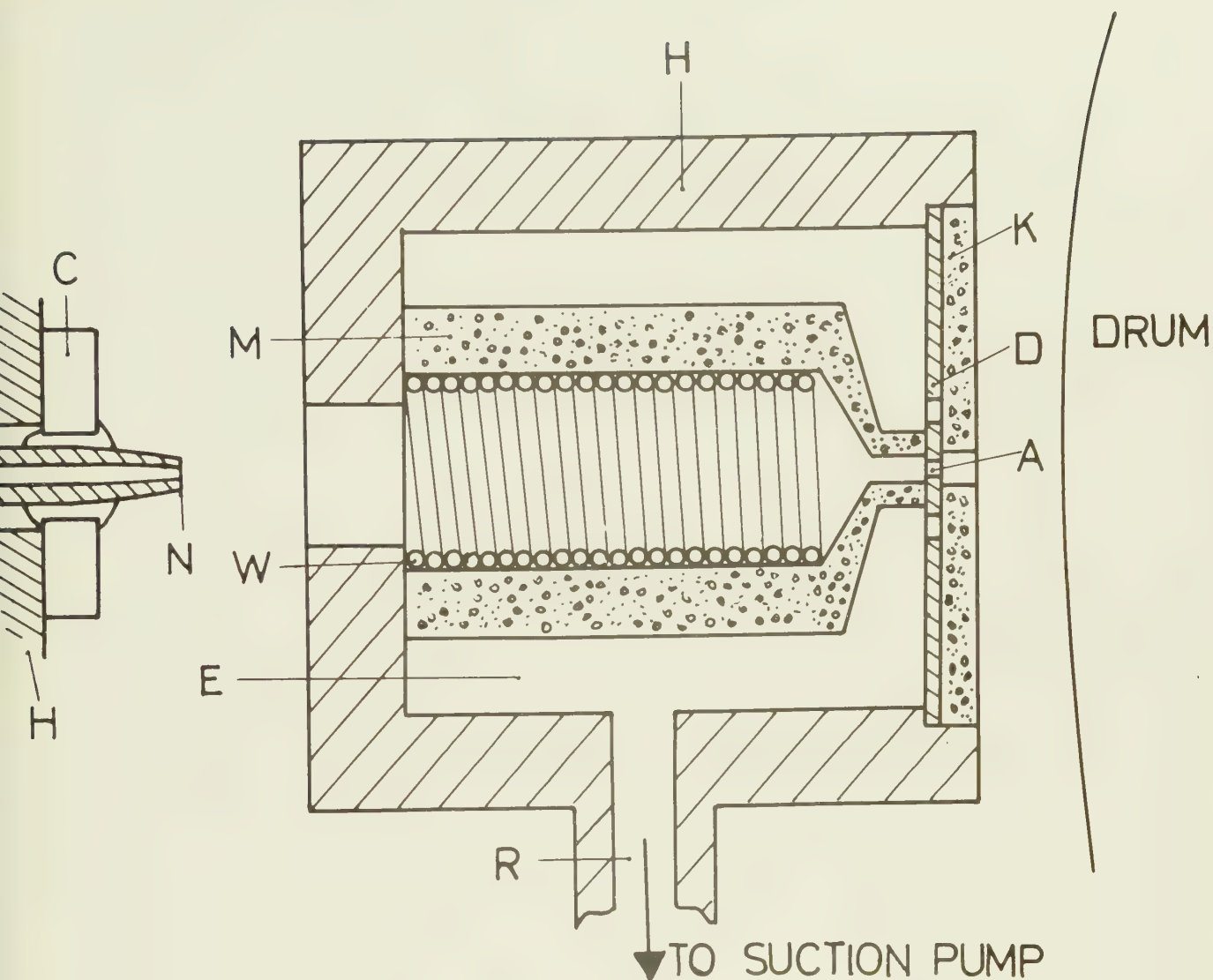


Fig. 2:25. The structure of the control electrode. A tube M of porous material the inner side of which is electrically conductive is connected to the metal housing H, to which the control voltage is applied. The charged ink drops are partially intercepted by the tube and the diaphragm D and then sucked away by a vacuum maintained inside the housing.

The control electrode E is composed of a brass housing H to which the control voltage is applied. It contains the aperture A, a fine hole in a thin brass plate D, enclosed by a ceramic porous material in the shape of the tube M and the disk K. The tube M absorbs the ink drops of the spray, thereby keeping the aperture free from ink while the disk K collects drops which have changed their direction due to collisions with the aperture walls. It also collects drops thrown back from the recording paper because of their high velocity when striking the paper. By means of a suction pump the ink is then removed from the porous material via the channel R. To prevent the generation of electrostatic charges by charged drops, which hit electrically insulated parts, the inside of the porous tube M is covered by a tightly wound helix of copper wire W, which is connected to the brass housing.

In order to be able to restrict the control voltage to values below about 1000 V, the electrode length must increase with the nozzle diameter since larger drops require a larger distance for the spray to develop enough to produce a neglectable background in the recordings. Typical values of the electrode length are 10 - 12 mm for a 10 μm nozzle and 14 - 16 mm for a 15 μm nozzle with an aperture diameter of 0.3 mm if an ink pressure of 30 kp/cm^2 is to be used.

3. DETERMINATION OF THE UPPER FREQUENCY LIMIT OF THE INK JET DEVICE

3.1. Experimental procedure

The upper frequency limit of the modulation of the ink jet, i.e. the number of times the jet can be turned on and off per second is evidently of crucial importance for all applications which make use of the intensity modulation method. This frequency limit is a measure for the maximum number of dots that can be recorded on the paper during one second. Because of the fundamental importance of this quantity for the sharpness, grey scale capability and other qualities of images generated by the ink jet device, a special investigation of this quantity was made. As will be shown below this investigation involves certain compromises which make it difficult to express the frequency limit in the form of a single figure.

Before making the actual investigations suitable experimental parameters have to be selected for the experiments. Since the final objective of the present paper is to investigate the image reproduction capabilities of the ink jet method, these parameters are selected in such a way that they equal those used in ink jet devices, which were found to be most appropriate in various applications. Here certain compromises have to be made as will become clear by the following considerations.

It can be shown that the frequency limit is strongly dependent on the voltage on the control electrode switching the jet into the "off" state, i.e. generating the spray. This is due to the repulsion between the large edge drops at the beginning and the end of each drop train constituting a pulse, which was already mentioned in chapter 2. Obviously the charge on these edge drops is increasing with the voltage applied to the control electrode and thus the repulsive forces on and between these drops increase too. This effect is especially noticeable with short "on" pulses, resulting in short drop trains of only 10 drops or less, in which case the large edge drops may be displaced out of the axis of the jet to such an extent that they cannot pass through the aperture of a diameter of only 0.3 mm at the farther end of the control electrode shown in Fig. 2:25. In this case the "pulse" may be lost completely and no dot is recorded on the recording pa-

per. Because of this it is desirable to decrease the control voltage in the "off" state as much as possible.

On the other hand, a low "off" control voltage increases the background produced on the recordings since the ink spray is not as well developed as with higher control voltages (cf. Fig. 2:13). Obviously a compromise has to be found here between these two requirements which are of importance for the imaging quality of the system. Therefore, in each of the following experiments made with jets of different diameters, the control voltage was chosen in such a way that the background density measured with the reflection densitometer described in section 5.5 was approximately 0.10. This voltage will be called $U_{0.10}$ in the following. In order to give an idea of the influence of a change in control voltage, the results obtained at a voltage differing from this voltage $U_{0.10}$ with $\pm 20\%$ will also be presented.

Due to the aerodynamic stabilization of the jet discussed earlier in this paper, a series of short trains of uncharged drops travelling with only a short distance between each other will reach the recording paper more easily than if the intervals between the drop trains are large. In order to make a "worst case" investigation these intervals were, therefore, chosen so large that practically no aerodynamic interaction between the drop trains could take place. Preliminary experiments have shown this to be the case if the time difference between two pulses was 200 μs or more.

For the investigation glass capillaries with nozzle diameters of 7, 10, 15 and 20 μm were used, both with and without mechanical vibration control of the jet. A test pattern was produced with each of the ink jets generated with these nozzles for the three different control voltages defined above in the following way.

A good quality paper was fixed to a recording drum shown in Fig. 4:1 which had a diameter of 62 mm. Since the drum rotated with 900 rpm the surface speed of the drum was 3 m/s. The voltage supplied to the control electrode was then adjusted to such a value that the background did not exceed the value given above.

Using a gated pulse generator, a pulse train with a constant pulse duration and a repetition frequency of 5 kHz was applied to the control electrode. In this way ink markings were produced on the recording paper, the

distance between two consecutive markings being 200 μ s. The duration of the pulse train was chosen in such a way that a single recording line was obtained the length of which was somewhat less than the circumference of the drum. Each recording line was made with a different "on" pulse duration, which was varied from about 40 μ s to 2 μ s in steps of about 5 μ s. In this way, one test pattern was obtained for each pulse duration for later evaluation. Further, in the same way test patterns were produced for control voltages 20% higher and 20% lower than the most suitable voltage $U_{0.10}$ producing the background density of 0.10 as described above.

The test patterns thus obtained consist of lines of dots, one line for each pulse duration. For the longest pulse durations all dots are perfectly recorded in all experimental runs while with shorter durations of the "on" pulses some of the dots on the test pattern are missing. As will be shown in the following this decrease in the number of successfully recorded dots occurs at different pulse durations for different nozzle diameters and voltages.

The parameter combinations for the various nozzle diameters used in these experiments are presented in Table 3.1. In all electrodes an aperture diameter of 0.3 mm has been used.

Nozzle diam. (μ m)	Ink pressure (kp/cm ²)	Drop formation frequency (MHz)	Voltage $U_{0.10}$ (V)	Voltage $U_{0.10}$ (Controlled drop form.) (V)	Electrode length (mm)
7	36	1.50	700	400	8
10	30	1.03	1000	900	10
15	26	0.75	1000	1000	16
20	24	0.57	1100	1100	20

Table 3.1.

No efforts were made to determine optimal parameter combinations for the four nozzle diameters, but they were chosen with regard to earlier experiences. However, it has been observed, that within reasonable limits, a parameter change which positively influences the upper frequency limit has to be counteracted by a change of negative influence if the background suppression is to be preserved. Thus, for example, if the voltage $U_{0.10}$ would still be able to provide the desired background suppression, an increase in e.g.

pressure has to be counteracted by the use of a longer control electrode.

3.2. Results

The number of successfully recorded dots was counted for a length of 6 cm of the recording line for every pulse duration. Since the surface velocity of the drum was 3 m/s, 100 dots were found in the sample if all dots were correctly printed by the ink jet device, while for the shorter pulse durations less dots were counted since some of the dots were lost. Using these measurements, curves were plotted for each nozzle diameter showing the number of successfully recorded dots as a function of pulse duration and the duration at which the dot count had fallen to 50% of the maximum number (100) was determined. Since we think that these 50% values can be used as significant figures for the upper frequency limit of the ink jet device, these values are plotted against nozzle diameters both for the most suitable voltage $U_{0.10}$ and for values 20% above and below this value. These results are given in Fig. 3:1 and Fig. 3:2 which show this relation for ink jets without and with control of the drop formation process by mechanical vibrations. From Fig. 3:2 we see that using a 7 μm nozzle and controlled drop formation a dot can be placed on the recording paper by a 3 μs pulse with a probability of 50% if a background density of 0.10 is accepted.

The 50% values given in Fig. 3:1 and Fig. 3:2 do not give any information about the pulse duration at which a probability of practically 100% is obtained for the printing of a dot. From the evaluation of the test patterns used for this investigation it can be concluded, that this pulse duration is about twice as long as that of the 50% value. Thus, for a 7 μm jet using controlled drop formation the 50% value is 3 μs and the 100% value 6 μs while a 10 μm jet without drop control needs an increase from 8 to 16 μs to make sure that all pulses are really recorded on the paper. However, for obvious reasons the 100% value is much less well defined than the 50% value which explains the use of the 50% value in Fig. 3:1 and Fig. 3:2.

On the Figures 3:1 and 3:2 the influence of controlled drop formation by mechanical vibration of the jet is clearly evident. Thus, using drop control by vibrations, much shorter pulses can still be successfully recorded. The importance of this fact for image reproduction will be demonstrated by the investigations on image quality and graininess of grey shades described below, which show that the definition of the images is increased by controlled drop formation and the graininess reduced.

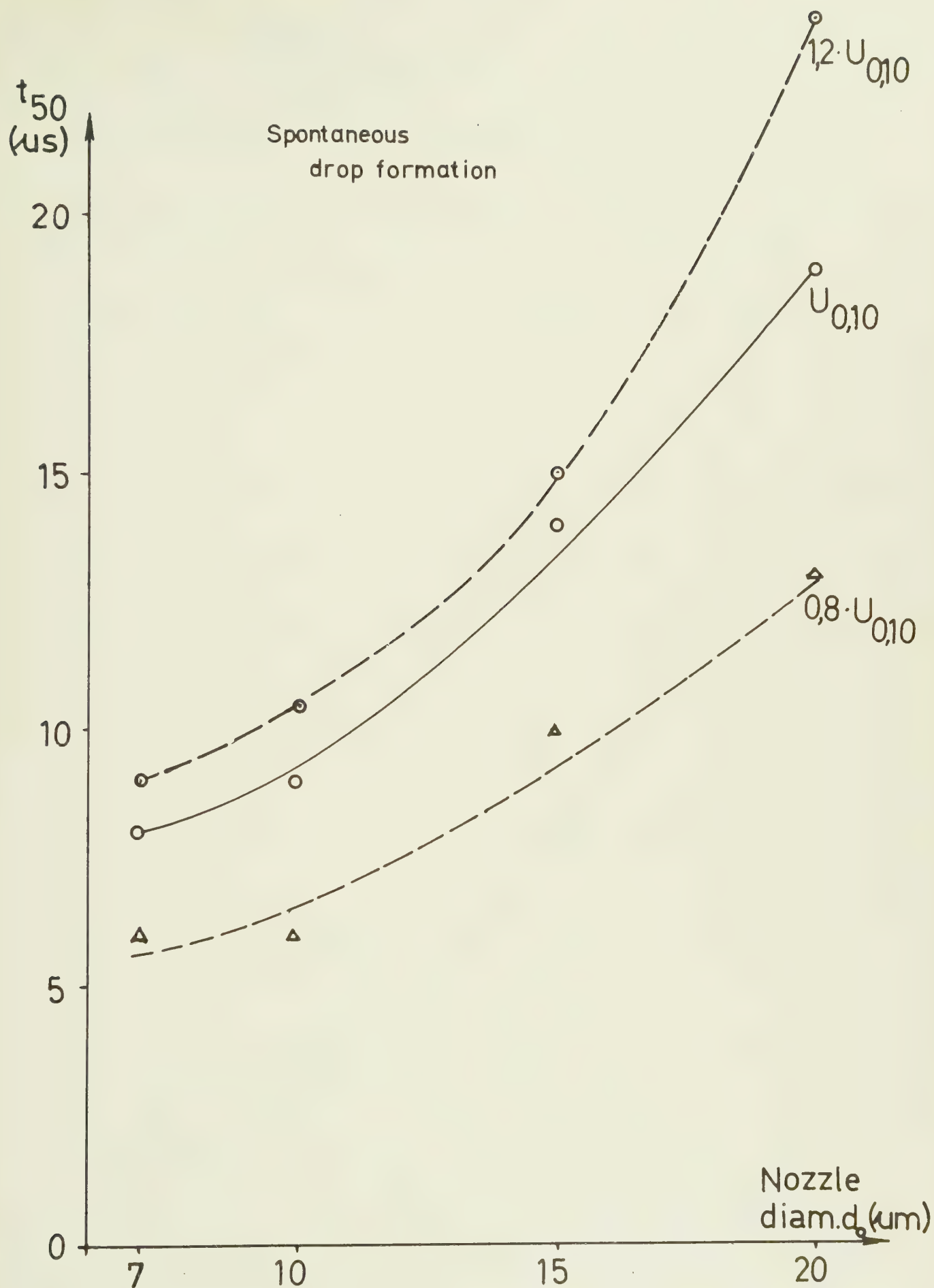


Fig. 3:1. Minimum pulse duration t_{50} at which dots can be recorded with a probability of 50 % as a function of nozzle diameter. No control of drop formation by mechanical vibrations.

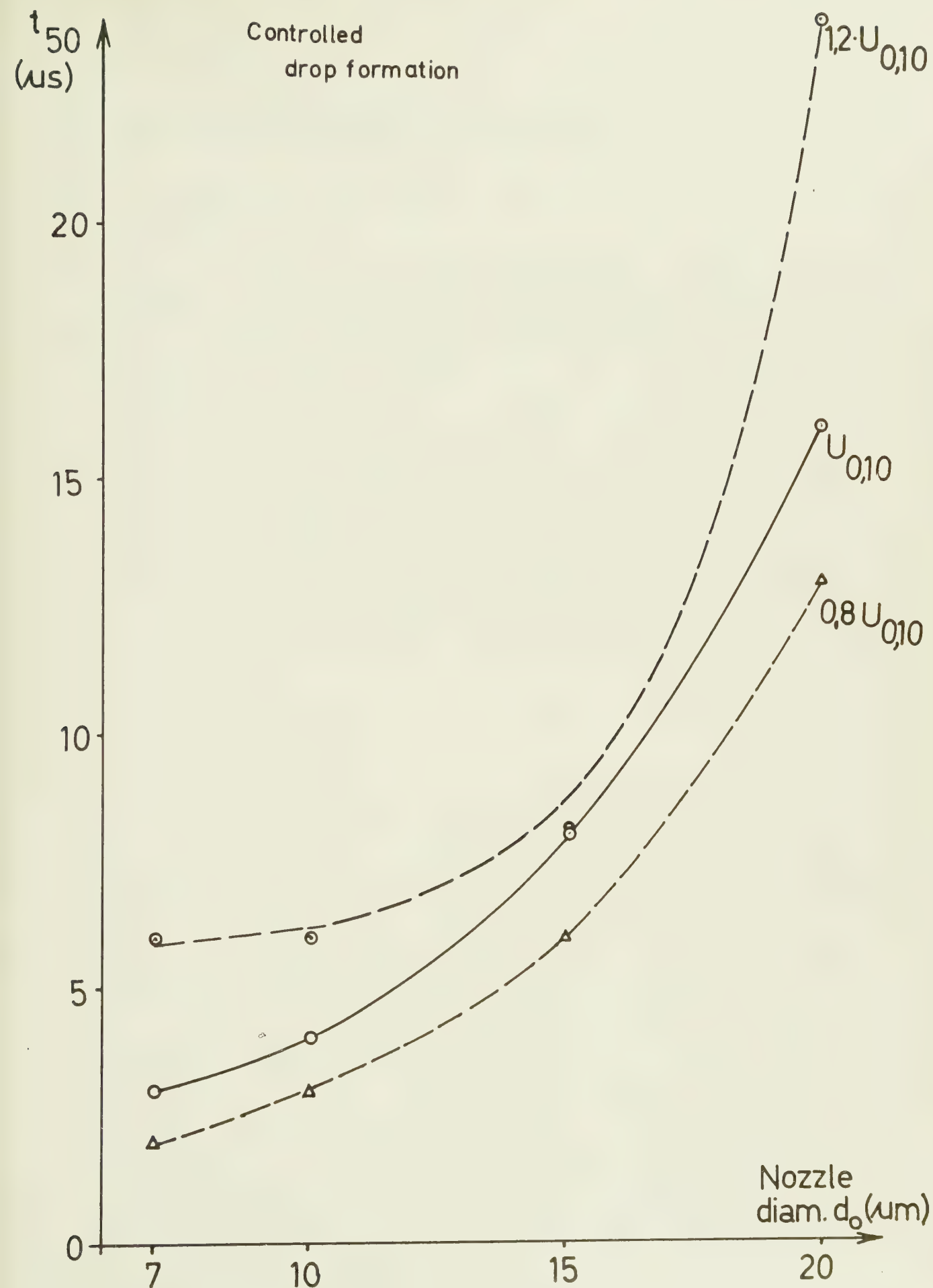


Fig. 3:2. Minimum pulse duration t_{50} at which dots can be recorded with a probability of 50 % as a function of nozzle diameter. Drop formation controlled by mechanical vibrations.

4. PRELIMINARY EXPERIMENTS ON IMAGE REPRODUCTION

4.1. Introduction

An obvious application of the recording process, described above, is generation of images consisting of a line pattern similar to that of a TV-picture. While the TV-picture consists of closely spaced lines with varying brightness due to the intensity of the electron beam scanning the fluorescent inside of the TV-screen, the image produced by an ink jet is built up of closely spaced intensity modulated recording traces. The intensity of the traces may then be varied and controlled by different types of signal sources. The simplest way to obtain such a source is to scan an original image line by line with the same velocity as the reproduction is made and convert the signal from the scanning device into a suitable form for the control of the intensity of the trace. In this way the method could be utilized for a line by line image reproduction.

4.2. Experimental apparatus

Preliminary experiments have been made by means of equipment shown in principle in Fig. 4:1. For the reproduction of high quality pictures two drums, D_1 and D_2 , both with a diameter of 62 mm were placed on the same axis and driven by a synchronous motor M at a speed of 15 revolutions per second. Using a screw drive connected by cog wheels to the axes of the drums not shown in the figure, this motor moved the drums simultaneously and slowly sideways in the direction of their axes at a speed of 0.1 mm for each revolution. Hence the scanning line density of the experiments described below was 10 lines/mm if another line density is not expressly mentioned. The original to be reproduced was fastened on drum D_1 , while D_2 held the recording paper. When the drums were turned by the motor M, the original on drum D_1 was scanned line by line by a photoelectrical system consisting of the photomultiplier L and the microscope objective O combined with an illumination device (Leitz Mikroskopobjektiv für Auflichtbeleuchtung UO11/0.25, 11 $\times$). After amplification, the electrical signal generated by the photomultiplier L is applied to a control electrode E shown in Fig. 2:25 of the ink jet intensity modula-

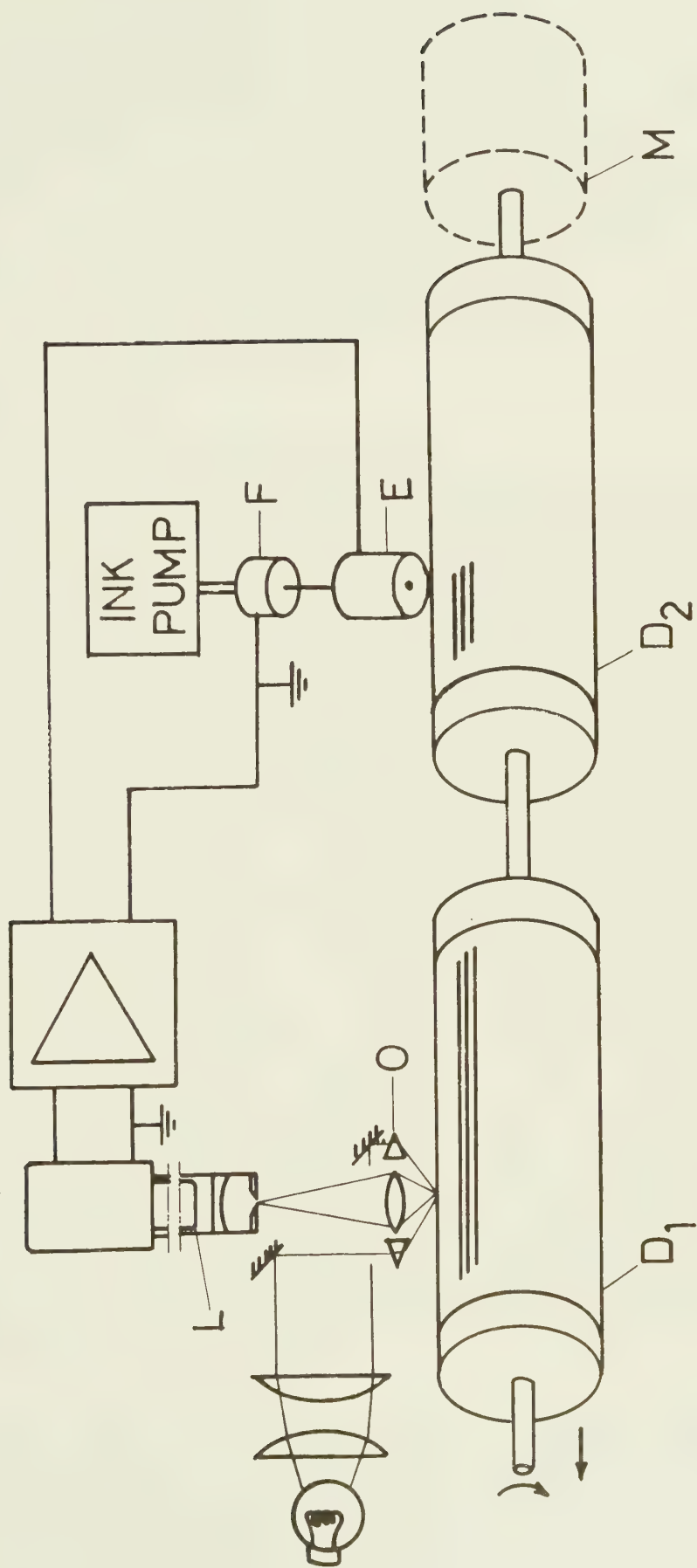


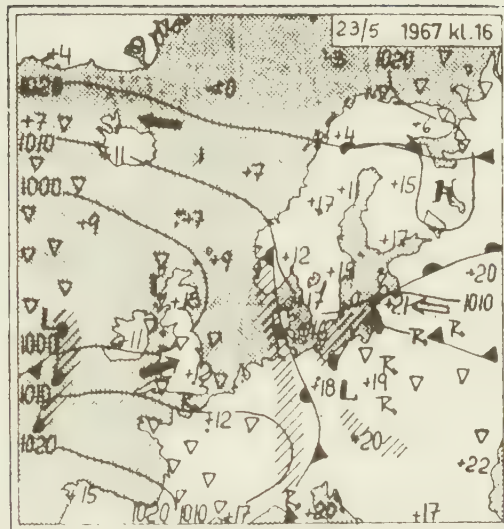
Fig. 4:1. Principle of experimental apparatus.

tion system described in chapter 2. In this way the original image will be reproduced on the recording paper on drum D_2 line by line. The ink is supplied to the system via the filter housing F by the ink pump. In all the investigations described here blue ink provided by the Elema-Schönander Company, Stockholm, has been used if not otherwise stated. This ink was of the same type as that used in the "Mingograph" ink jet oscillograph produced by said company except for the dye concentration which was three times as high as that of the oscillograph ink.

4.3. Results

The quality of the images reproduced in this way is dependent on several parameters of the reproduction process. If only the definition is considered, the diameter and the velocity of the jet, the surface speed of the recording paper on the drum and the line density of the scanning procedure are of great importance. The use of a small jet diameter in conjunction with a low surface speed and a high line density gives images of a high definition. This is demonstrated by the reproduction in Fig. 4:2 which was produced with a jet from a $10\text{ }\mu\text{m}$ nozzle with a jet speed of 30 m/s on an apparatus using two rotating drums as described above (Fig. 4:1). The surface speed in this case was 3 m/s and the scanning line density 10 lines/mm . The main drawback of an apparatus using these parameters is a relatively low image production rate, since 200 seconds are needed to print an image of A4-size. Increasing the jet diameter makes it possible to increase the surface speed and decrease the line density and thus increasing the image production rate. The reproduction shown in Fig. 4:3 was obtained with a $20\text{ }\mu\text{m}$ jet with a surface speed of 8 m/s and a scanning line density of only 4 lines/mm , resulting in a production time of 30 seconds for an A4-page. Comparing Fig. 4:2 and Fig. 4:3 it can be easily observed, that the definition is appreciably decreased in the latter reproduction. Further, in spite of the larger diameter of the ink jet used in the latter picture, the density of the print is appreciably reduced at the same time resulting in a decreased contrast.

In order to estimate the suitability of the method for image reproduction it is important to obtain objective quality criteria for the various properties of the reproduced image. The properties, which are important for the image quality are the density range of the grey scale, the tone-reproduction capabilities, the definition and the graininess. The density range



r Polen fördjupas och rör sig norr ut, liksom tillhösom på tisdagskvällen täckte södra Östersjön och Götaland. Norr om lagtrycket råder en tilltagande

Fig. 4:2. Reproduction of black and white original by ink jet. Surface speed 3 m/s, scanning line density 10 lines/mm, jet diameter 10 μ m.

Fig. 4:3

jet diameter is 20 mikrometer and the text is produced on a drum line by line with a surface speed of 8 m/s and a line density of 4 lines/mm.

Fig. 4:3. Reproduction of black and white original by ink jet. Surface speed 8 m/s, scanning line density 4 lines/mm, jet diameter 20 μ m.

ought to be as great as possible, to give as large differences as possible between light and dark areas of the image, which is a necessary prerequisite for obtaining a good contrast. The tone reproduction capabilities should be such that the grey shades of the original image will be correctly transferred to the reproduction. Further, a good definition is required to make it possible to reproduce small details of the image. Finally, the graininess shows up as a random variation of the density in areas of the image with constant average density and thus limits the definition of the reproduced image beyond which it is not possible to determine if an observed density variation is real or due to random variations.

Since the subjective quality of the image produced by an ink jet approaches that of the photographic process it is suitable to use the same methods for the measurement of the quantities mentioned above, that are used for objective quality determination of photographic material. In the following these measurements will be discussed.

The investigation of the quality of the reproductions made in the following chapters of this report will be mainly concerned with prints obtained on an apparatus using a surface speed of 3 m/s and a scanning line density of 10 lines/mm. However, even certain measurements on reproductions obtained with higher surface speeds will be described for comparison.

5. PRODUCTION OF GREY SHADES

5.1. Introduction

For all types of reproduction methods, the ability to reproduce grey shades is of large importance. This is especially true for the method studied in this paper, since it has also the ability to copy colour images if three ink jets using magenta, yellow and cyan ink are operated simultaneously. In that case a suitable mixture of the density produced by these three ink jets at a certain point on the recording will allow the production of any shade of almost every colour. However, an obvious requirement for this is that the grey shades produced by the ink jet can be continuously controlled. Because of this an appreciable effort was made to develop and investigate two different methods to produce grey shades with the modulated ink jet method studied in this paper. These methods will be described in the following.

5.2. Voltage mode method

It was already mentioned in chapter 2 of this paper that the top angle of the ink spray shown in Fig. 2:1b can be continuously controlled by the signal voltage applied to the control electrode. Thus, using an electrode structure as illustrated by Fig. 2:25 as the control electrode, the number of ink drops reaching the recording paper through the small aperture at the farther end of the electrode structure can be determined by the signal voltage. This fact can be used to control the density of the recording trace produced on the paper by the signal voltage, since the amount of ink producing the trace decreases with increasing signal voltage. In the following this technique will be called the "voltage mode method".

The voltage mode method does have certain disadvantages, one of which stems from the fact that the width of the recording trace is determined by the diameter of the aperture in the control electrode structure. For good definition, therefore, an aperture having a diameter as small as 0.1 to 0.2 mm is required. Obviously, the reliability of an electrode structure using apertures as small as that is decreased since this requires a very high degree of stability of the direction of the jet. Further, suitable precautions

have to be taken to avoid that the aperture is closed by dust or an excessive amount of ink, that cannot be sucked away fast enough by the suction pump. Further, it will be shown below that the voltage mode does not easily allow an exact control of high density grey shades. Because of this, another method to produce grey shades was developed.

5.3. PDM mode method

This method uses a pure on-off modulation of the ink jet and produces grey shades in a way similar to the matrix method commonly used in the graphic industry, where the amount of printing ink transferred to the paper is determined by the size of the matrix points. A similar effect can be obtained by modulating the ink jet by voltage pulses having a constant repetition frequency. The duration of these pulses determines the amount of ink deposited on the recording paper and thus the density of the record. Therefore, this method will be called Pulse Duration Modulation mode (PDM mode) in this paper. A greatly magnified view of different grey shades obtained with this method is shown in principle in Fig. 5:1.

The grey scales described below which have been generated by this PDM mode are produced by pulses which are supplied to the control electrode with a repetition frequency of 10 or 18 kHz. Thus the width of these pulses can be 100 or 55 μ s at a maximum corresponding to a maximum length of the trace segments of 0.3 or 0.17 mm if the surface speed of the recording paper is 3 m/s. By controlling the duration of these pulses the amount of ink received by the recording surface can theoretically be controlled from zero (white) up to full amount of available ink (black). Thus, it should be possible to obtain any grey shades by controlling the pulse duration in a suitable manner as shown in Fig. 5:1. Although this method has the advantage of a more reliable control of the intensity of the trace (on-off method) some physical limitations of the spray forming process seriously restrict the theoretical grey scale capability of the PDM mode as will be further discussed in section 5.7 below.

5.4. Determination of the reflection density

In order to obtain a good half tone reproduction by means of the ink jet recorder, an investigation of its grey shade characteristics had to be

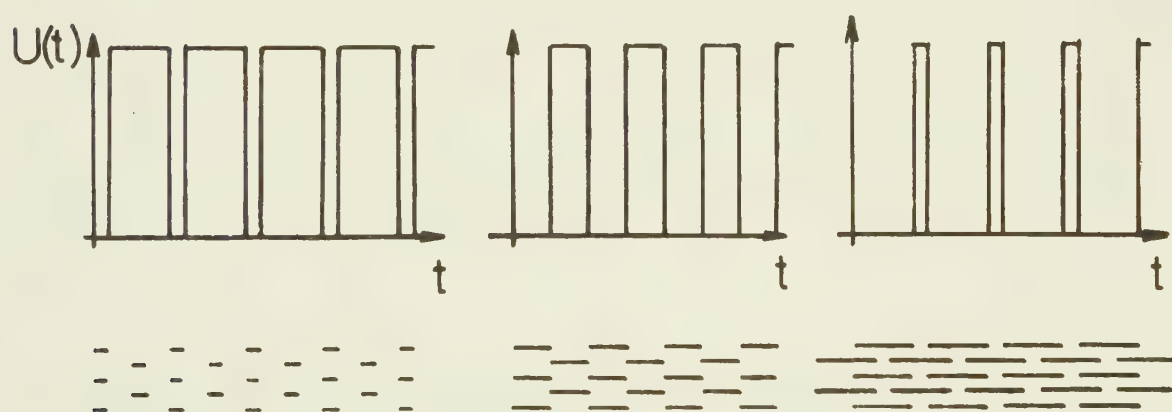
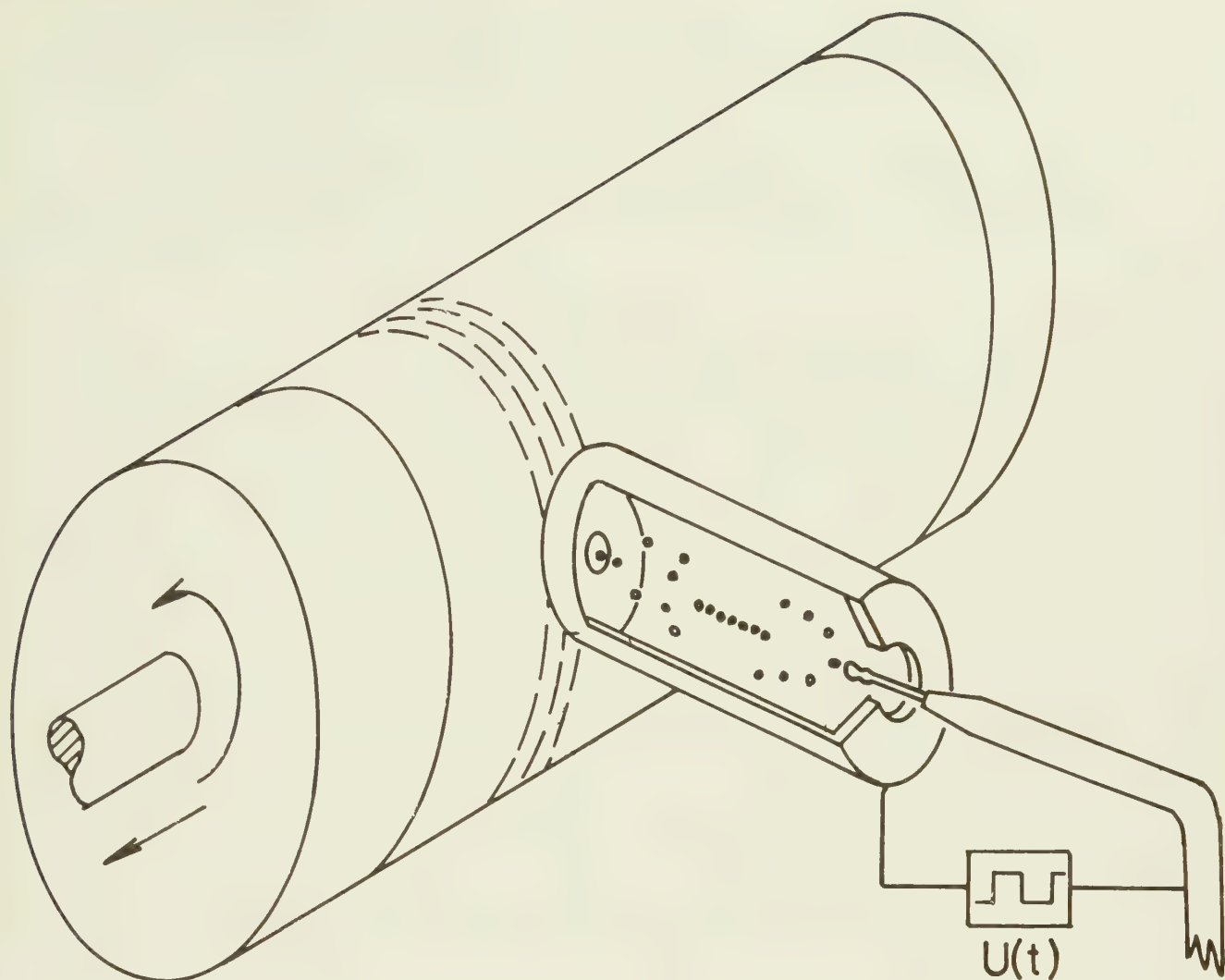


Fig. 5:1. Principle of PDM mode method. The amount of ink deposited on the paper is determined by the duration of the "on" pulses, thereby creating different grey shades. The upper part of the figure shows the principle of the method while in the lower part the time dependence of the control voltage $U(t)$ as well as the magnified appearance of three different grey shades obtained with these signal voltages is given.

carried out. Before describing these investigations existing definitions for reflection density measurements will shortly be reviewed (Tupper 1966).

If light of an intensity of I_o is directed towards a surface and the intensity of the reflected light is I_1 then the definition of the reflectance R of the object is

$$R = \frac{I_1}{I_o}$$

Now, the reflectance R can either be based on the measurement of I_1 in only one direction or in several directions. The directed reflectance may vary much from point to point of the object due to the surface texture, while the undirected or diffuse reflectance averages these variations. Further, the reflectance can of course be measured as a function of the wavelength of the light by inserting suitable optical filters in the light beam.

The reflection density S is defined as the logarithm of the ratio I_o of the radiant flux incident on the sample to the part I_1 of the radiant flux which is reflected back by the sample:

$$S = {}^{10}\log \left(\frac{I_o}{I_1} \right) = {}^{10}\log \left(\frac{1}{R} \right)$$

where R is the reflectance of the sample as defined above.

This definition of the reflection density does not place any restrictions on the way of measuring the density. However, the measured value of the density depends strongly on the geometrical arrangement of the optical system used in the photometer. Therefore, as has been pointed out by Tupper (1966), it has become the practice in reflection densitometers to illuminate the sample in a direction perpendicular to the paper and observe and measure the luminance of the sample in a narrow cone at 45 degrees or vice versa.

5.5. Experimental method for the reflection density measurements

In order to obtain experimentally the density curves as a function of suitable parameters for both the voltage and the PDM mode, test patterns were generated by means of the rotating drum apparatus described in chapter 4 (Fig. 4:1). A recording paper, the desirable qualities of which will be described below, was fixed to the drum D_2 . The test pattern was then produced by rotating the drums at normal speed about 100 times

while all other parameters e.g. signal voltage and pulse length were held constant. Due to the simultaneous slow movement of the drums in the axial direction described above, a strip about 1 cm wide of a constant grey shade was generated on the paper. The density of this strip was then constant and only dependent on the electrode voltage in the voltage mode or the pulse length in the PDM mode, if stochastic fluctuations were disregarded. After this the electrode voltage or pulse length were varied in appropriate steps and another strip sample was recorded. In this way grey scale samples consisting of a number of parallel strips of varying grey shades were obtained on the same recording paper, each about 1 cm wide. An example of such a test pattern is given in Fig. 5:2.

Since the quality of the recordings was found to be strongly dependent on the quality of the recording paper, the influence of different surface properties of the paper, such as coating and whiteness, has been investigated. As a result of this a recording paper was finally selected for these experiments which produced a large density range of the recording. This paper should have a high whiteness and a low absorption of the ink drops which facilitates an extension of the density range in both the high and low ranges. A further desirable property is a smooth surface structure not introducing density variations by varying absorption or suction along the fibers of the paper. The paper which satisfied these requirements best was found to be the baryte paper, which is a coated paper kindly supplied to us by the Agfa-Gevaert Company, Leverkusen, Germany. This paper is normally used as a base material for producing light sensitive paper for photographic printing and enlarging. The coating of the paper consists of a suspension of barium sulfate powder in gelatin constituting an effective diffuse reflector. The paper, however, causes a certain bleaching of the ink jet recordings which increases with time. Because of this the production of the test patterns was immediately followed up by the density measurements.

For the measurement of the density a reflection densitometer of type MacBeth Quanta Log RD-107 R was used. This instrument measures the diffuse reflection density by collecting the portion of perpendicularly incident light reflected from a spot of the pattern with a diameter of 3.2 mm in an elevation direction of $45^{\circ} \pm 5^{\circ}$. This light falls on the cathode of a photomultiplier operated in a special circuit producing a linear density scale. Since the test patterns were made with blue ink, the red filter of the densitometer (Kodak Wratten 25) was used. However, our blue ink has not the same spectral composition as the cyan, which is normally used as one

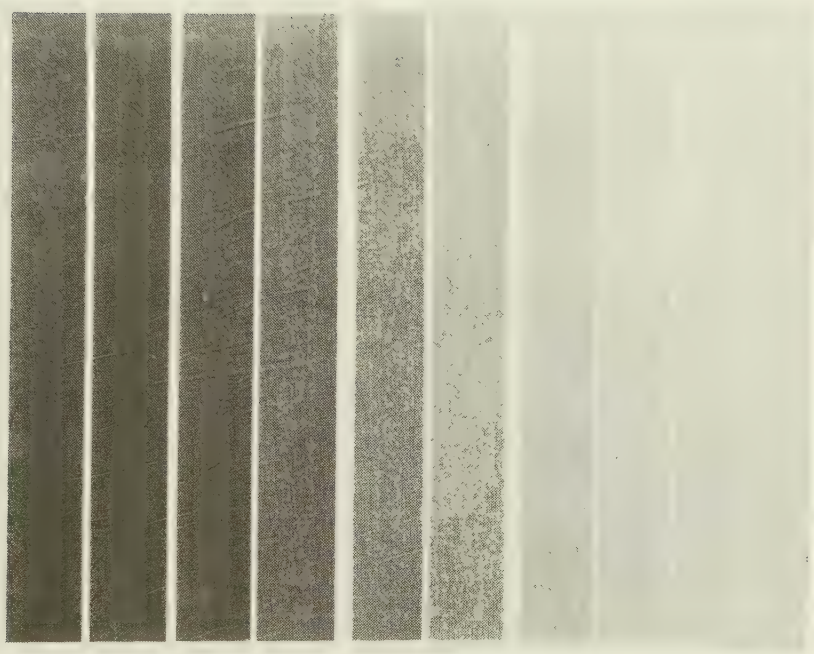


Fig. 5:2. Grey scale samples for the determination of the reflection density.

of three basic colours in colour printing and photography. Thus, since the filter of the densitometer is adapted to this colour our measured density values will be a little too low. This, however, does not change the shape of the density curves which depends only on the relative density values.

5.6. Reflection density curves for the voltage mode method

As described above, the grey shades of the record are determined only by the voltage applied to the control electrode of the ink jet device. Hence the only variable in producing test patterns with the voltage mode method is the magnitude of this control voltage. Because of this the density measured on these test patterns was plotted versus the control voltage in the graphs below.

The results of the reflection density measurements of test patterns obtained by the voltage mode method on baryte paper are shown in Fig. 5:3. Every one of the recorded points of the density curves is the average value of three measurements at different points of the sample. When producing the test pattern the drop formation of the 10 μm diameter jet was controlled by mechanical vibrations generated by a PZT-crystal oscillating with a frequency of 800 kHz.

It was mentioned above that the surface properties of the recording paper have a certain influence on the maximum density which can be obtained with the same ink jet device. This is demonstrated in Fig. 5:4 which shows reflection density versus control voltage of a test pattern which was recorded on normal typewriter paper. In this case all the ink jet parameters were the same as in Fig. 5:3 including the control of the drop formation process by mechanical vibrations.

The lower maximum density obtained with typewriter paper is explained by the high porosity of this paper which causes part of the ink to be absorbed into the paper and, therefore, a higher contrast can be attained on baryte paper. This effect is accompanied by a slight reduction of the definition obtained in images recorded on typewriter paper as compared with baryte paper. Obviously even this is due to the porous quality of typewriter paper but this decrease in definition is barely noticeable and thus of no importance except in very special applications.

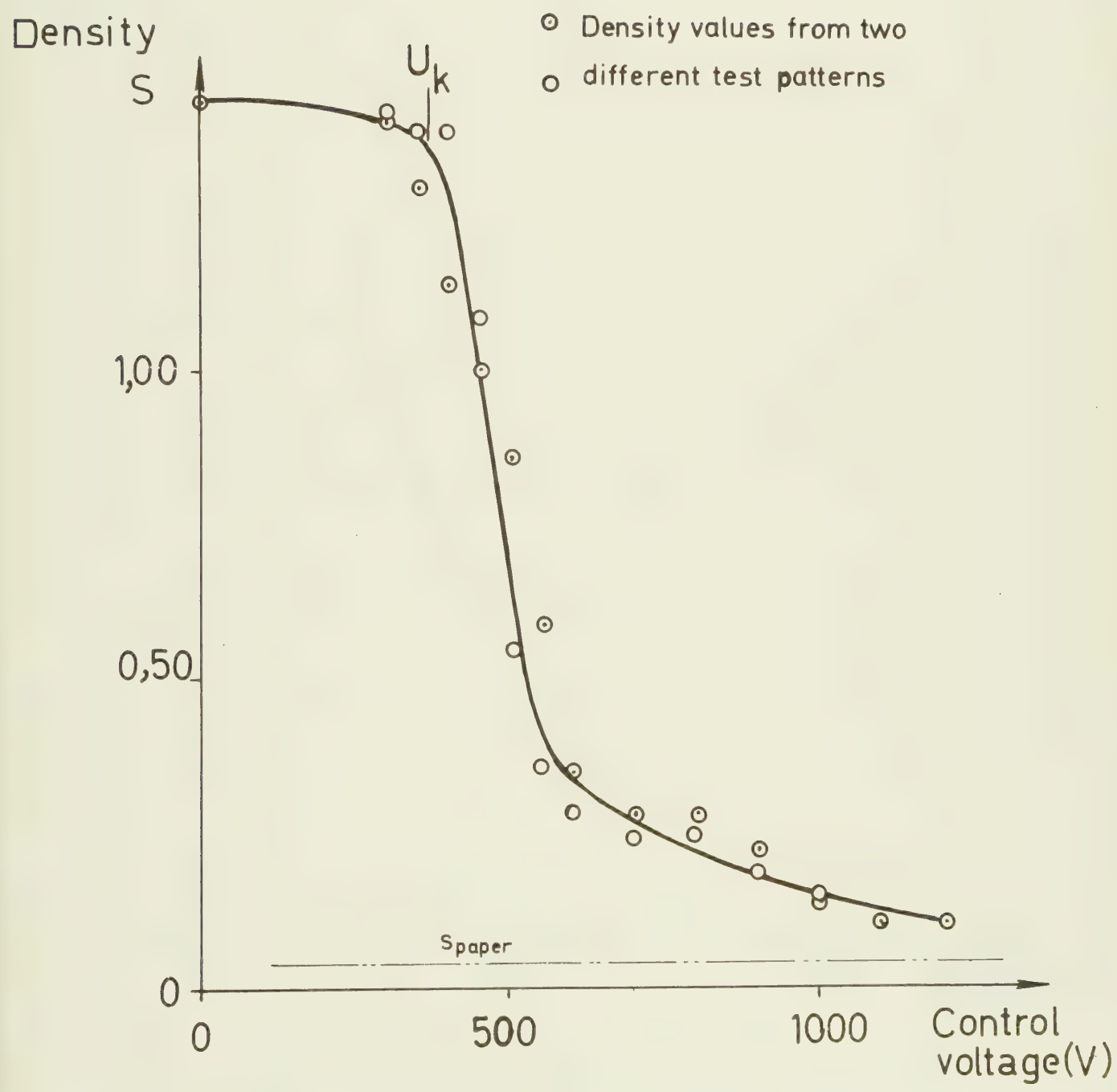


Fig. 5:3. Reflection density of grey scale patterns obtained by the voltage mode method. Ink jet diameter $10\text{ }\mu\text{m}$. Drop formation controlled by mechanical vibrations. Baryte paper.

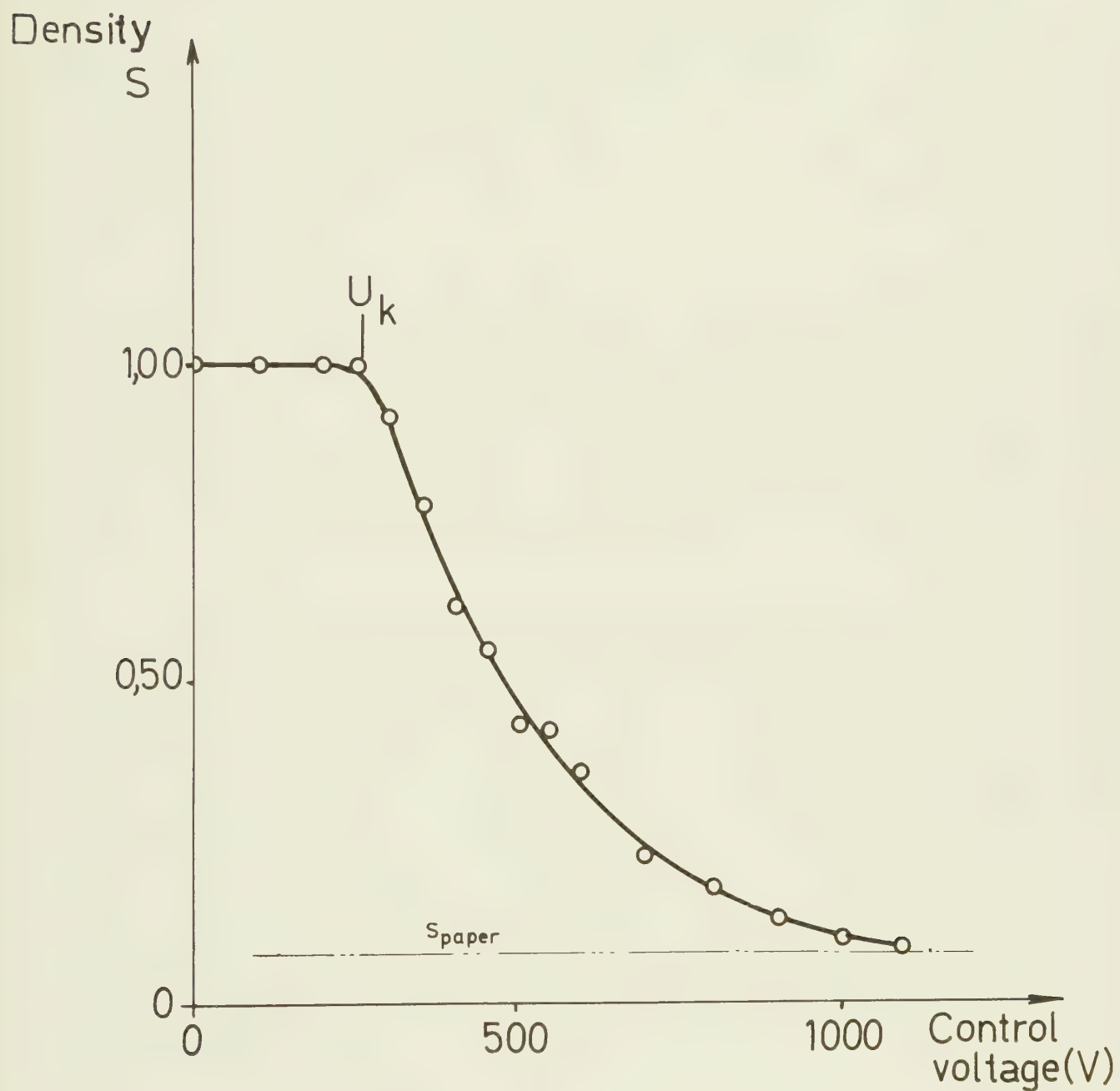


Fig. 5:4. Same as Fig. 5:3 except that common typewriter paper was used as record receiving surface.

The influence of mechanical vibrations controlling the drop formation process on the density curves obtained is illustrated by Fig. 5:5, which has been obtained with an ink jet device having the same parameters as that used in Fig. 5:3 but without the use of mechanical vibrations controlling the drop formation process. We see from the figure, that slightly smaller voltages are necessary to obtain a certain density value. This is due to the fact that the drop formation controlled by mechanical vibration results in drops of nearly equal size, very much in contrast to the uncontrolled drop formation (cf. Fig. 2:6 and Fig. 2:2). Because of this the stabilizing action of air friction is more effective in the former case, in which the equal sized drops follow exactly behind each other. Hence the jet breaks up into a spray at lower voltages if the drop formation is spontaneous.

The density curves given in Fig. 5:3 to Fig. 5:5 illustrate another property of the voltage mode method for the generation of half tones, which will later prove of importance for the application of this method in image reproduction. The curves show, that the reflection density obtained with this method is constant up to a certain voltage level U_k . Above this voltage the density at first decreases sharply with increasing voltage while for higher voltages this decrease is smaller.

This shape of the curves can be explained in the following way. Below the voltage U_k the spray is not developed and all drops pass the electrode aperture. When the control voltage is raised to such a value that the spray formation just begins, the velocity of the drops decreases since the drops no longer follow exactly after each other, which increases the aerodynamic drag on the separate drops. This fact results in a further increase of the spray angle due to the increase in time required by the drops to pass to the recording paper, which explains the rapid density decrease versus voltage in the beginning of the descending part of the curves. At higher voltages the spray formation has gone so far that the aerodynamic interaction between the drops is negligible because of which the density decrease is less abrupt.

The small increase in density between an electrode voltage of 0 V and 200 V in Fig. 5:5 is explained by the fact that for the lowest voltage adjacent recording traces do not overlap everywhere because of the irregular drop formation. Thus, white spaces are obtained between the lines. These spaces cause a decrease in reflection density which is not compen-

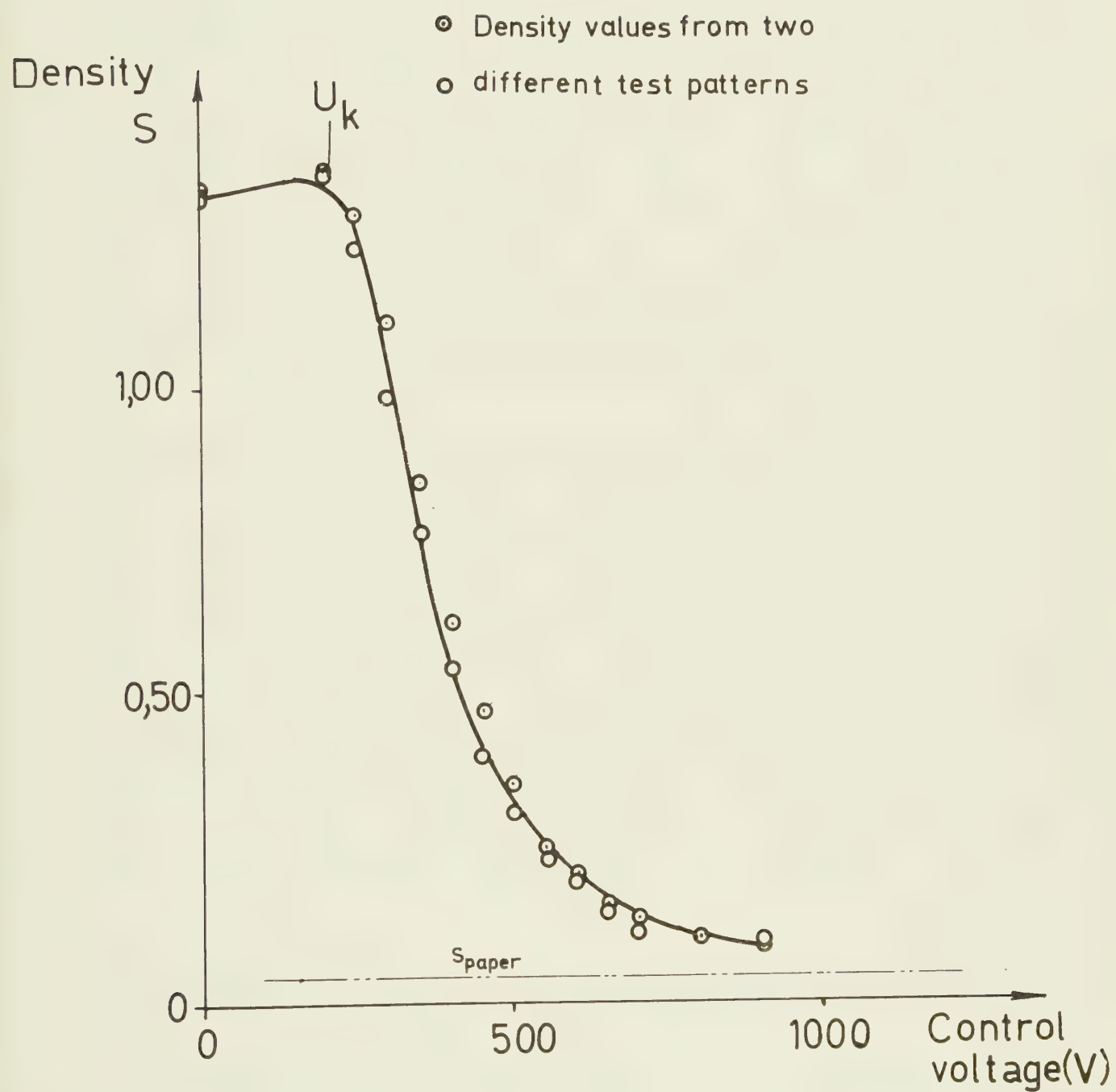


Fig. 5:5. Same as Fig. 5:3 but without drop formation control.

sated for by the denser part of the adjacent areas. When the electrode voltage is increased the trace width will be larger and a total overlap is obtained. The effect can be counteracted by choosing a higher number of traces per mm.

A closer study of the density curves as shown in Fig. 5:3 to 5:5 reveals a disadvantage of the voltage method for the generation of grey scales which impairs the usefulness of this method seriously in the high density range. In both of the figures 5:3 and 5:5 density values are plotted from two different test patterns which were made under exactly the same conditions. Thus it should be expected that the density values from the two patterns would approximately coincide for the same voltages on the control electrode. However, as can be seen in the figures, this is not the case. In fact, the differences in density for a certain electrode voltage are so great for the steep part of the curves that this part may hardly be considered reproducible. For lower density values the reproducibility seems to be better at least when a jet with spontaneous drop formation was used.

When applying the voltage method to a reproduction process this means that it is very hard to obtain reproducible grey shades. This is especially true for the steep part of the density curves, i.e. at high densities. In this part of the curve very slight changes in the parameters of the jet, e.g. jet velocity, surface tension or viscosity will greatly influence the density obtained at a certain control voltage. On the other hand, this influence is much less critical in the low density ranges where the slope of the density curve is much less. Because of the practical difficulties which were experienced during the earlier part of this investigation due to this fact, the PDM mode technique for the generation of half tones described above was developed. In the following the results of density measurements on test patterns generated by the PDM mode will be described.

5.7. Reflection density curves for the PDM mode method

Test samples for the investigation of the PDM mode method, which was described in section 5.3. were prepared in a way similar to those used in the measurements on the voltage mode method. Since the density obtained by the PDM mode method depends on the duration of pulses with constant frequency, a pulse generator with variable pulse width was synchronized to the drum rotation. After suitable amplification these pulses

were applied to the control electrode, thus switching the intensity of the recording trace on and off.

Even in this case the test patterns consisted of parallel strip samples about 1 cm wide, which were recorded side by side on the recording paper using a different pulse length in each strip sample. The pulse repetition frequency in these experiments was 10 kHz and the pulse length could be varied from 0 to 100 μ s. Since the amount of ink deposited on the recording paper can be determined in this way, the density of the record can be controlled. Therefore, in the following the density is plotted as a function of the electrical pulse length during which the ink jet is in the "on" position, i.e. when the control voltage is zero.

As before, the surface velocity of the drum carrying the recording paper was 3 m/s and baryte paper was used to obtain maximum contrast. Further, the drop formation process at the tip of the continuous jet was controlled by high frequency mechanical vibrations since this decreases efficiently the graininess of the record at low densities as will be shown in section 7.5.

In Fig. 5:6 a typical density curve obtained by the PDM method is shown. Here the reflection density is plotted **versus** the ratio between the "on" time t_{on} and the pulse repetition period τ . This curve was obtained from a test pattern which was recorded with an ink jet device having the following parameters: nozzle diameter 10 μ m, ink pressure 30 atmospheres, length of control electrode 12 mm and aperture diameter 0.3 mm. The pulse repetition period was 100 μ s resulting in a pulse width of the recording trace of 0.3 mm since the surface velocity of the paper was 3 m/s. The pulse voltage applied to the control electrode was 1000 V.

The Fig. 5:6 shows clearly that the density is highly dependent on the pulse duration, especially in the lower ranges of the reflection density. This implies that the grey scale is difficult to reproduce in this range. Further, it was found that the test patterns were very grainy for lower densities.

The reasons for these observations are the following: For lower densities only few drops in each pulse are allowed to reach the recording paper through the aperture in the control electrode. These originally uncharged drops always coalesce and combine with some adjacent charged drops as

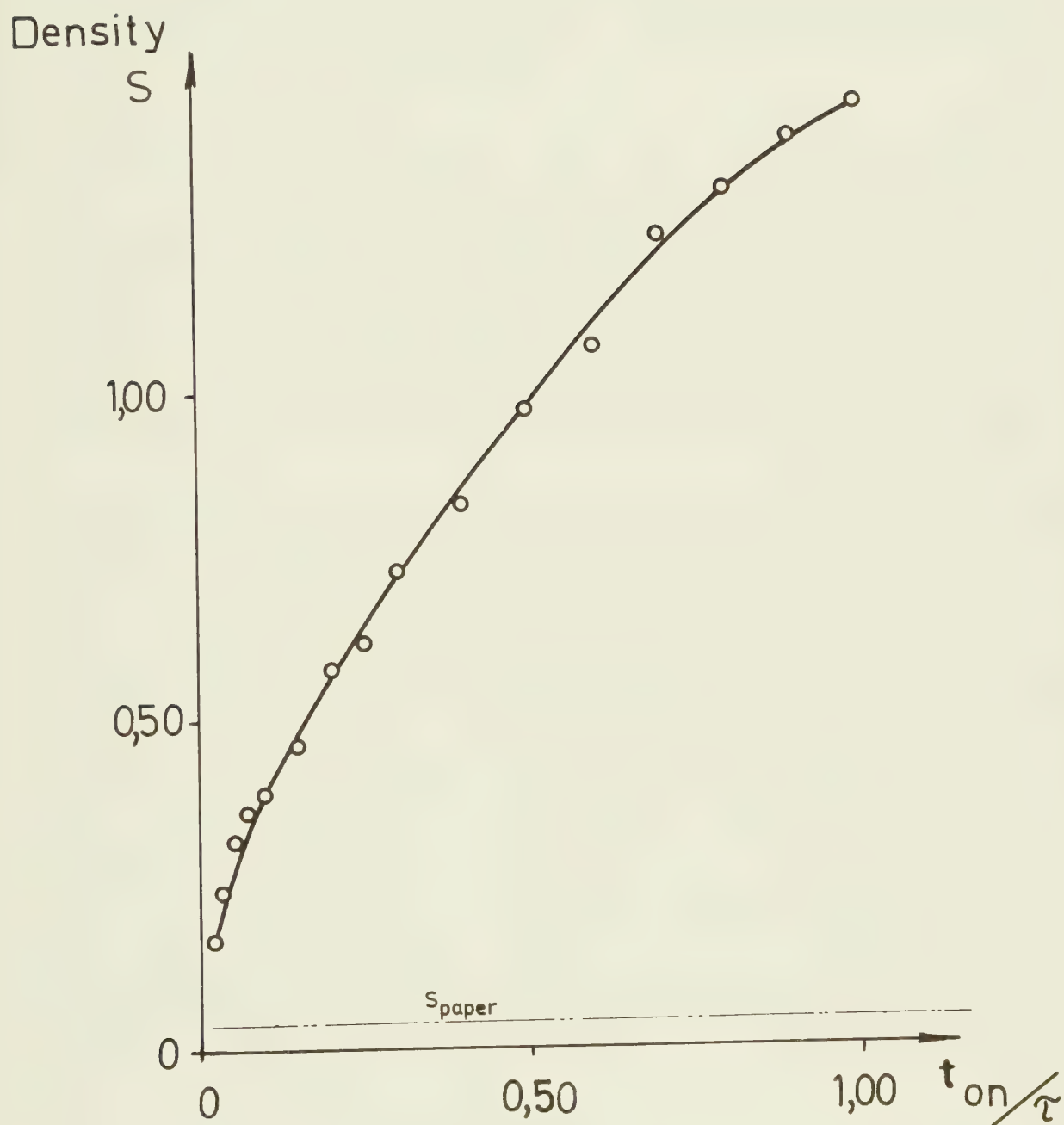


Fig. 5:6. Reflection density obtained by the PDM mode method as a function of the PDM ratio t_{on}/τ . t_{on} is the duration during which the control voltage is zero and τ the pulse repetition period.

illustrated in Fig. 2:15. Some of these charged larger drops will be repelled out from the jet axis due to their charge and are consequently stopped by the aperture while others are only slightly affected and reach the recording paper. This was already discussed in section 3.1. Obviously this is a stocastic process which will result in an irregular deposition of large drops on the paper and explains, therefore, the strong graininess of the record observed at low densities. This effect is easily observed with "on" pulse durations of less than about 10 μ s. Below this value not all of the "on" pulses reach the recording paper.

On the other hand, if the "on" pulses are longer than 10 μ s, the geometrical distance between the large edge drops of the drop train of each pulse becomes larger. Therefore, the repulsive forces between them is smaller which results in a stabilization of the drop train so that all the edge drops pass through the aperture and hit the paper (cf. section 3.2). Hence, at higher densities the pulse duration ratio is relatively well transferred to the paper and the graininess is reduced so much that the higher density ranges produced with the PDM mode are quite acceptable to the naked eye.

Unfortunately, the use of the PDM mode method for the generation of low density records is further impeded by another property typical for very short ink jet pulses. In chapter 2 it has been mentioned that it is impossible to generate pulses consisting of less than five original drops, since the high charge to mass ratio of the drops makes them diverge from the jet axis, thus never reaching the paper. Because of this fact, "on" pulses having a duration of less than 3 μ s do not create any recording trace on the paper. Thus, the density curve abruptly drops to zero at pulse durations of less than 3 μ s and a discontinuity of the grey scale in the low density range is created. This discontinuity as well as the strong graininess obtained with pulse durations between 3 μ s and 20 μ s cannot be accepted if a good quality of the record is desired. Because of this a combination of the PDM mode method with the voltage mode method discussed earlier will be considered in the next section.

5.8. Combination of the voltage and the PDM mode methods

After the analysis of the reflection density curves for the voltage mode and the PDM mode method it seems evident that none of the methods is suited for grey shade reproduction throughout the entire density range. How-

ever, since the main difficulties encountered with the voltage mode method were concerned with the production of the darker grey shades, while the quality of the PDM mode method was decreased in the lighter shades, it seems reasonable to try the methods in conjunction, so that the PDM mode covers the darker portion of the grey scale while the lighter portion is generated by the voltage mode. This can be achieved by producing the grey shades below a certain density level S_0 by means of the voltage mode and the darker shades by the PDM mode. A grey shade reproduction utilizing this combination method requires a special electronic circuit, which performs the switching between the two modes of operation at the density level S_0 . A suitable electronic circuit for this is schematically shown in Fig. 5:7.

The input video signal to the circuit, which may be derived by amplification of the photomultiplier signal from an optical image scanner, is fed into a comparator together with the reference voltage U_0 . At the same time the signal is connected to the PDM circuit and the analog gate II. If the voltage of the video signal exceeds U_0 , the comparator closes the analog gate II and opens gate I, which transfers the video signal to the analog OR-gate circuit in the final amplifier for voltage mode modulation of the intensity of the recording trace. When, on the other hand, the input voltage is lower than U_0 , the comparator closes gate I, which transmits the output signal from the PDM circuit to the OR-gate in the final amplifier for PDM mode modulation of the ink jet. Simultaneously gate II is opened resulting in a removal of the video signal from the input of the OR-gate.

The reflection density level at which the switching between the two methods of ink jet modulation takes place may be varied by a suitable choice of the voltage U_0 applied to the voltage comparator. Further, to ensure continuity of the density curve and its derivative at the switching point, an extra amplifier stage with variable amplification as well as level controls is inserted in the signal path of the voltage mode method.

It was pointed out above that for the generation of the darker shades of grey the PDM mode was to be used. Since, in this method, the pulse duration of the electrical signal controlling the ink jet is dependent on the density of the original, a special electronic circuit has to be devised that converts the video signal from the photomultiplier into pulses of suitable length. In the following the function of this PDM circuit, which is indicated in Fig. 5:7 as a block only, will be described.

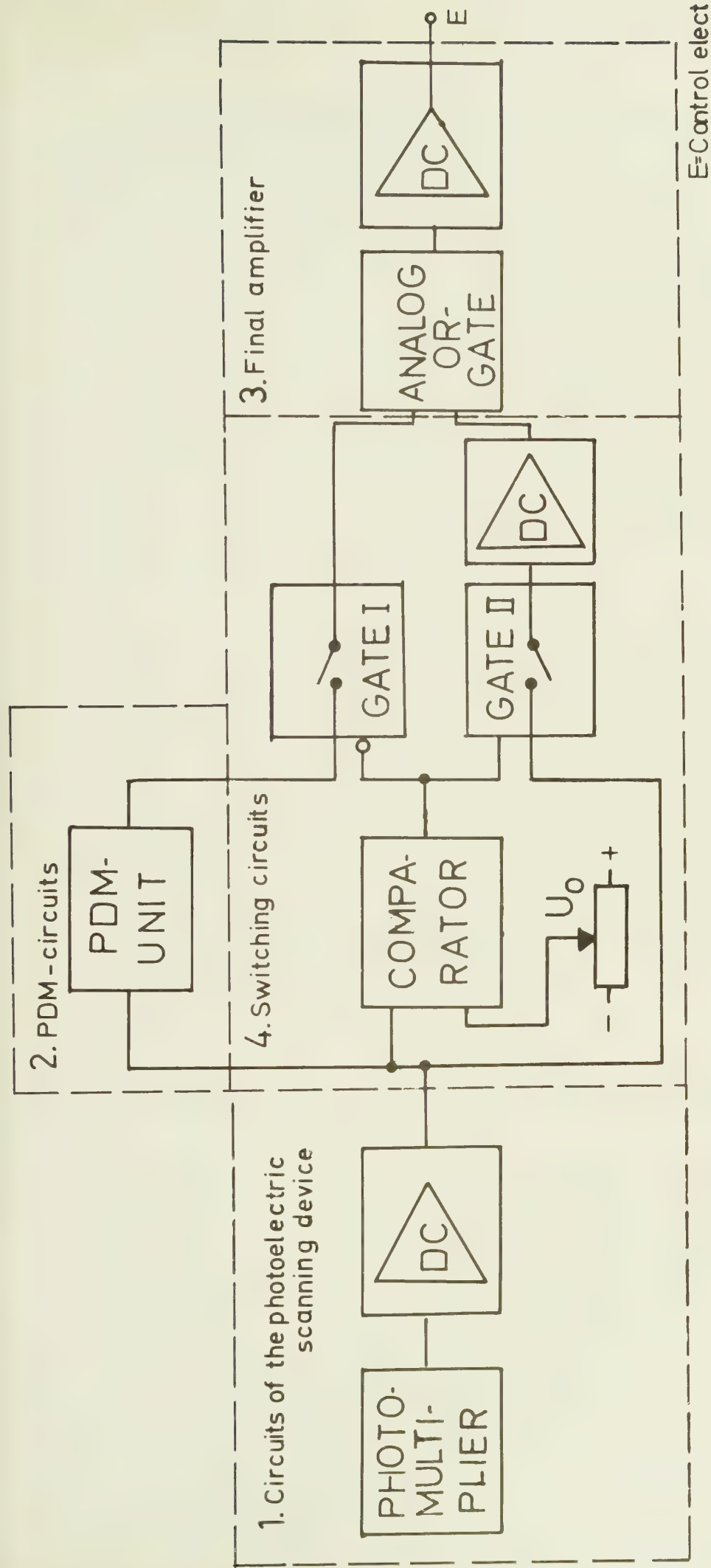


Fig. 5:7. Block diagram of the combination mode method. For the circuit description of the dashed blocks see section 5.9.

Fig. 5:8 shows the block diagram for this circuit. Here a non-linear ramp voltage obtained by integrating a saw-tooth signal is compared with the video signal (cf. Fig. 5:7) in a comparator. After the ramp voltage has returned to zero voltage the comparator output is high, which corresponds to the "off" state for the ink jet. Thus no recording trace is obtained on the paper until the ramp voltage and the video signal equal each other. Thereafter the comparator output voltage falls to a voltage level corresponding to the "on" state for the recording trace, and stays in this level until the ramp voltage falls to zero again. From this it is clear that the length of the pulses created by this circuit is dependent on the video voltage applied to the input of this PDM circuit in such a way that a low video signal, which is emanating from the darker portions of a scanned original picture, is transformed into a high "on/off" ratio for the recording trace while a high video signal results in a low "on/off" ratio.

It was already mentioned that the ramp voltage used in the PDM circuit was obtained by integrating a saw-tooth signal with a repetition frequency equal to the PDM pulse repetition frequency. This procedure was chosen in order to compensate for the shape of the reflection density curve as shown in Fig. 5:6. Compared with the linear saw-tooth signal, the integrated ramp increases the slope of the curve describing the dependence of the density on the signal voltage for the highest densities. Thus the parameters determining the form of the integrated ramp can be used to introduce a rough correction of the grey scale characteristics in those parts of the scale, where the PDM mode is used for the generation of grey shades, i.e. above the density S_0 defined above.

5.9. Electronic circuits of the combination mode method

Since the electronic circuits which have been used for the three modulation methods are included in the block diagram in Fig. 5:7, this diagram may serve as a starting point for a more detailed description of the circuits. Considering the fact that combinations of various parts of the electronics are used in **all** of the three modulation methods, a division into the following circuit blocks was found to be suitable:

1. Circuits of the photoelectric scanning device
2. PDM-circuits
3. Final amplifier
4. Switching circuits

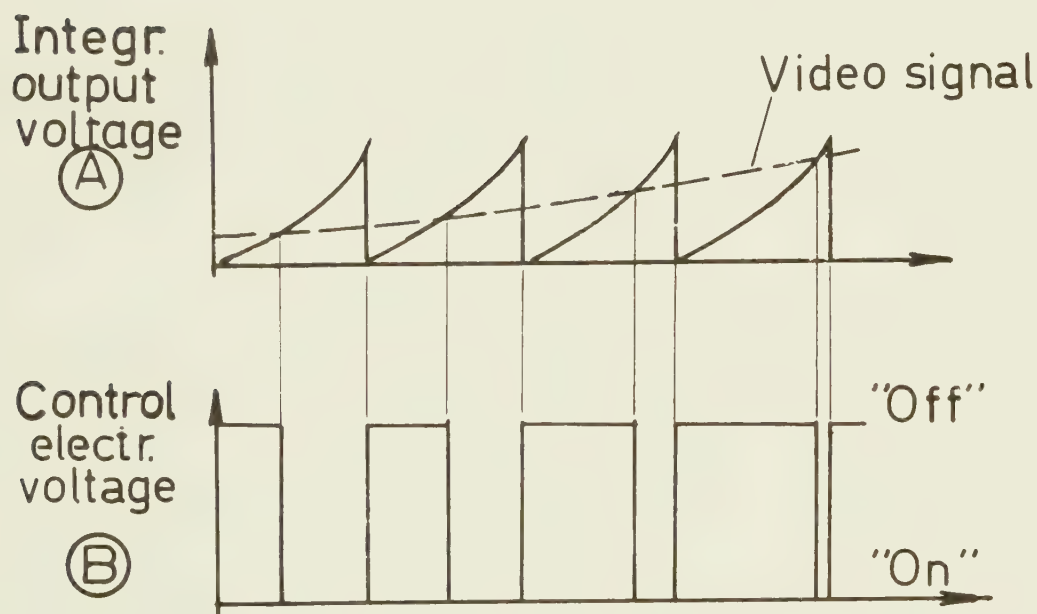
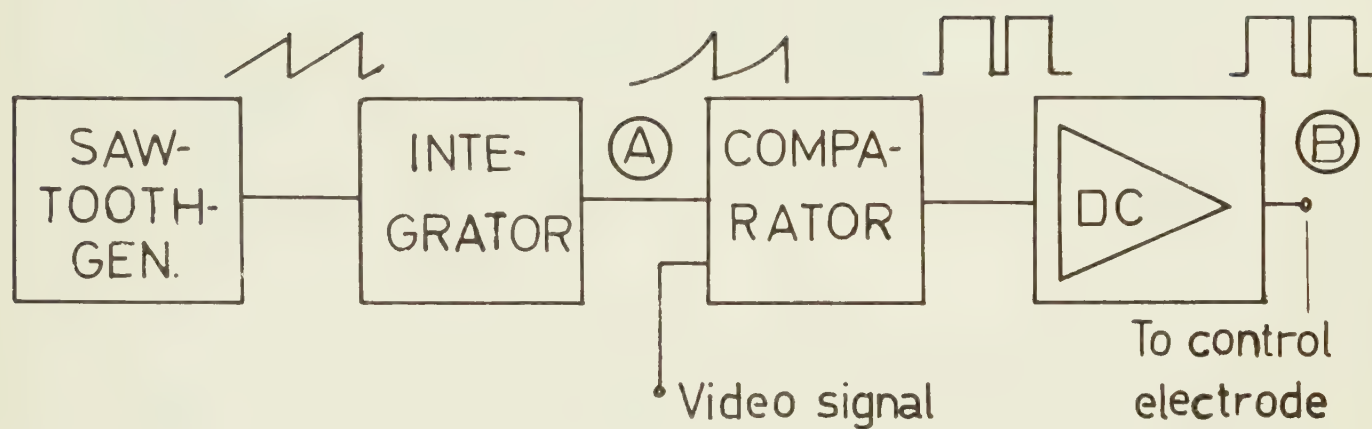


Fig. 5:8. Block diagrams of PDM circuit. At the points A and B of the circuit the voltage signals A and B shown below the block diagram can be observed.

Thus, of these four blocks, 1 and 3 are used in the voltage mode method, 1, 2 and 3 for the PDM mode and all four blocks for the combination mode method. A description of each of the blocks will be given below.

5.9.1. Circuits of the photoelectric scanning device

The preamplifier for the detector of the scanning device is shown in Fig. 5:9. A photomultiplier was used as the light sensitive element of the detector. For the scanning of black-and-white images, a Philips XP 1110 photomultiplier tube was used, while the scanning of three-colour originals was done with an XP 1117 because of the extended spectral sensitivity in the red of the latter tube. These tubes have a high output impedance and act as current generators.

For the present purpose the output current from the multiplier tube, which may be as low as some nanoampères, should be amplified by a factor of 10^6 without considerable distortion in a frequency range from DC to about 100 kHz in order to make sure that the image quality obtained is limited only by the upper frequency limit of the ink jet device and not by the amplifier circuits. This is also the reason for using a photomultiplier as light detector in the present experiments: phototransistors, although rather light sensitive, might impair the image quality because of their relatively low frequency limit, which is of the same order as that of the ink jet device.

To obtain the necessary frequency characteristics of the preamplifier, a series of operational amplifiers was used, each stage having a relatively low amplification. Further, due to the low photomultiplier current driving the preamplifier, a highly stable amplifier has to be used in its first stage. Because of this a chopper stabilized operational amplifier Burr Brown 3071/25 with a unity-gain bandwidth of 10 MHz was used as a current amplifier in the first stage. The feed-back resistance R_1 which determines the current amplification may be varied by a factor of 11. The DC-level can be varied by adding a current to the preamplifier input by means of the variable resistor in the "level" resistance network.

Since the demand for high stability can be reduced after the amplification in the first stage, the following stages employ conventional operational amplifiers. The second stage includes the vernier gain control and allows a certain frequency compensation by the connection of a peaking-capacitor.

PREAMPLIFIER

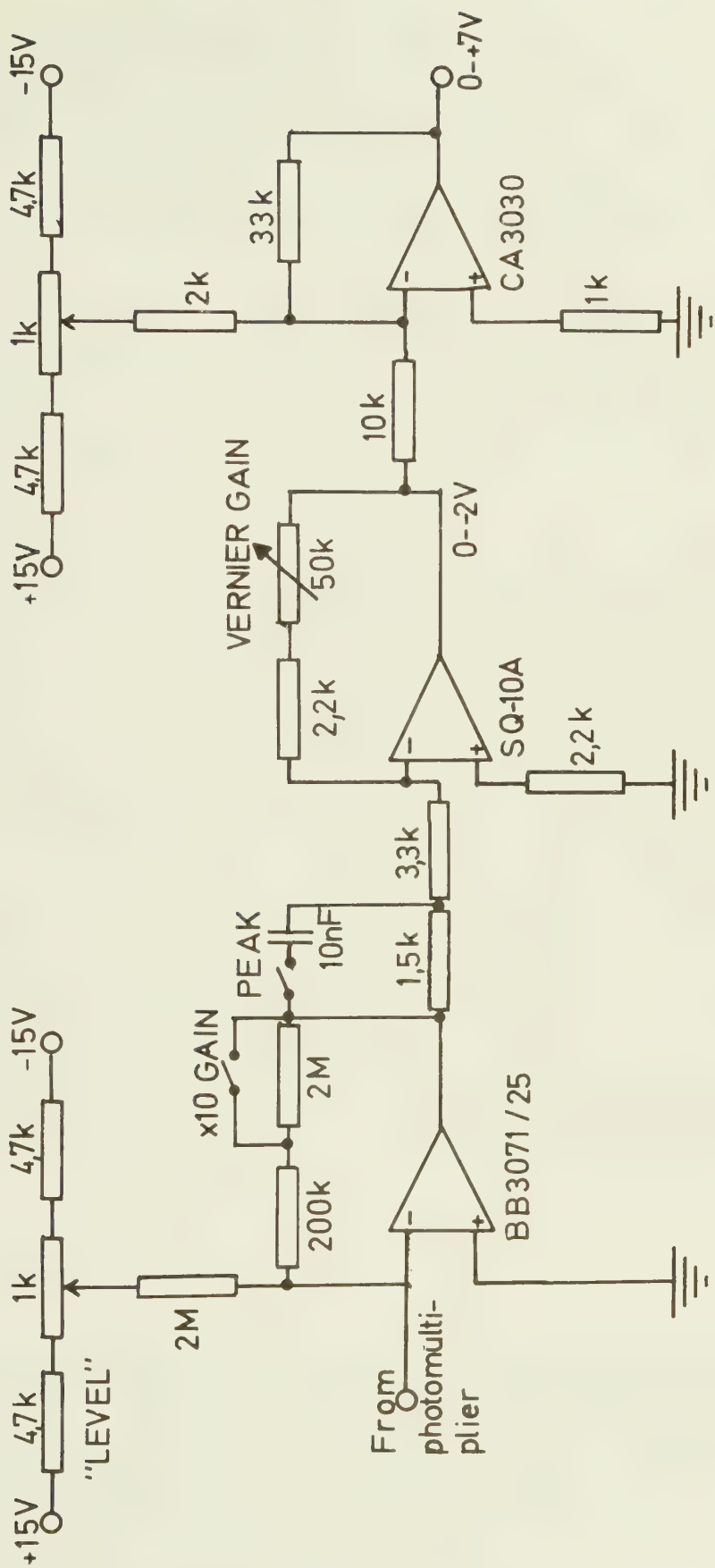


Fig. 5:9. Diagram of preamplifier.

The maximum voltage gain of this stage is a factor of 10. The gain controls of these two stages were adjusted in such a way that the video signal after amplification extended from 0 volts for the darkest parts of the scanned original image to -2 volts for the lightest. In the third amplifier this signal was then amplified to an output voltage range from 0 to + 7 volts.

If grey shades are to be generated by the voltage mode only, this output signal may then be inverted and corrected for its DC-level in an amplifier stage not shown in Fig. 5:7. The output signal of this amplifier is then connected through the analog OR-gate of the final amplifier to the control electrode of the ink jet device (cf. Fig. 5:7).

Alternatively, it may be connected also to the PDM circuits and switching electronics, in which case the half tones are generated by a combination of the two modes of modulation as described above. If this combination mode technique is used, the output of the preamplifier is connected to the PDM mode and voltage mode circuit simultaneously and the switching circuit determines which of the two modes of operation controls the ink jet at each instance.

The data of the preamplifier are given by

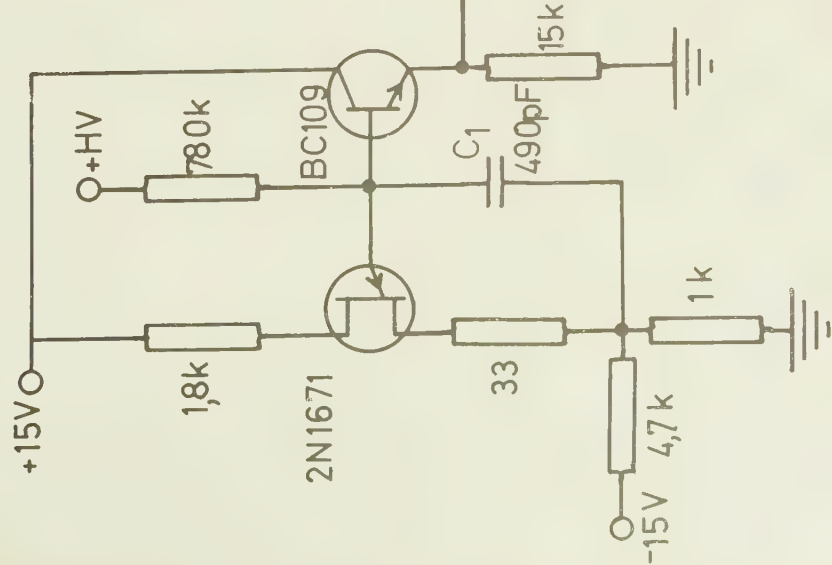
Current amplification (max.)	$3 \cdot 10^6$	
Rise time (Amplification: $3 \cdot 10^5$):	15 μ s	
Fall time (Amplification: $3 \cdot 10^5$):	15 μ s	
Stability: Versus temp.	20 mV/ $^{\circ}$ C	referred to output
Versus time	5 mV/h	referred to output

5.9.2. PDM-circuit

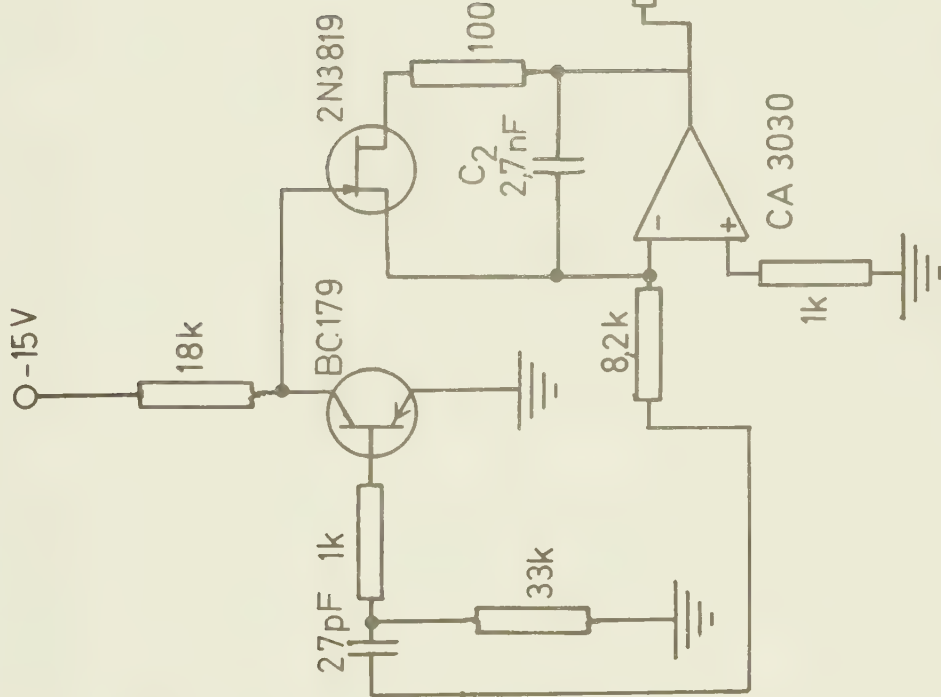
The purpose of the PDM-circuit is to modulate the pulse duration of a pulse train of constant pulse repetition frequency with the video signal. At the same time a correction of the grey scale characteristics is to be introduced to correct for errors in the reproduction of the reflection density due to the characteristics of the ink jet device.

A suitable circuit for this is shown in Fig. 5:10 and consists of three main parts, namely a linear ramp generator, an integrator and a comparator followed by an impedance adaption stage.

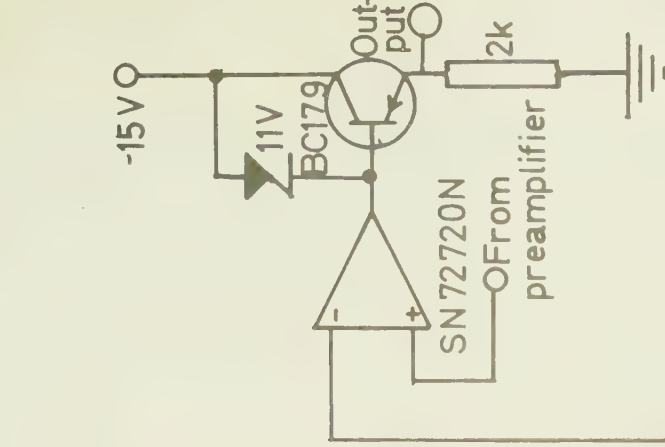
PDM-CIRCUIT



Ramp generator



Integrator



Comparator

Fig. 5:10. Diagram of PDM circuit.

The ramp voltage is generated by charging the capacitor C_1 from a high voltage source (≈ 50 V) with a suitable time constant until the unijunction transistor 2N1671 fires at a capacitor voltage of approximately 5 V and discharges the capacitor with a very small time constant through its emitter-base junction and the 33Ω -resistance. Thereafter the capacitor C_1 recharges again etc., which results in a periodic cycle. By making use of only a small part of the nonlinear charging characteristics of the capacitor an approximately linear ramp voltage is obtained. Through an emitter follower this voltage is then fed into the integrator.

The input signal to the integrator is also utilized for the discharge of the capacitor C_2 of the integrator by means of a FET transistor. This is necessary at the end of each period of the input signal in order to keep the DC-level of the integrator constant. To achieve this, the signal from the ramp generator is applied through an inverting amplifier stage to the FET transistor 2N3819 after being differentiated in the RC-network, whereby the FET is made to conduct at the end of each period of the ramp generator. In this way, the voltage at the output of the integrator starts from the same zero point at the beginning of each period and increases roughly with the square of the time, thereby providing the non-linear ramp voltage required for the correction of the grey scale characteristics. This voltage is then inverted and applied to the negative input of a comparator, where it is compared with the video signal from the preamplifier output.

Now, if the video signal exceeds the ramp voltage, the output of the comparator will be held at -4 volts, while it is decreased to -15 volts in the opposite case. Because of the voltage inversions taking place in the switching circuits and the final amplifier following this PDM circuit, the -4-voltage at the comparator output corresponds to the "off" state of the jet and vice versa. Thus a pulse train is generated by the PDM circuit, the pulse length of which depends on the density of the original image as measured by the video signal and gives rise to a recording trace generated by the ink jet as outlined in Fig. 5:1. For the adaption to the switching circuits, the comparator is followed by an emitter follower.

5.9.3. Final amplifier

The output of the final amplifier stage is directly applied to the control electrode of the ink jet device and thus controls the ink jet. It con-

sists of an analog OR-gate in cascode with a pentode as shown by Fig. 5:11. The OR-gate consists of two identical transistors coupled in parallel and connected to the pentode via a resistor. A resistive feed back provides temperature compensation of the transistors. The anode resistor of the pentode circuit allows a maximum current of 60 mA at a supply voltage of 1000 volts.

If both of the transistor amplifier inputs are grounded both transistors are cut off and consequently also the pentode. When one of the inputs is raised, the current through the circuit increases gradually until the pentode is fully conducting with an anode current of 60 mA, which results in a voltage drop in the $130\ \Omega$ -resistance of approximately 8 V, which balances the grid voltage, thereby providing the appropriate condition for a fully conducting valve. The value of the $130\ \Omega$ -resistance is not critical, however, it should not be chosen too low, since this would lower the upper frequency limit of the amplifier.

In order to optimize the frequency response it is of importance to decrease the capacitive load at the output of the amplifier as much as possible. Because of this the final amplifier stage was mounted in the immediate vicinity of the ink jet device to keep the connection to the control electrode as short as possible. The rise time for the final amplifier stage is obviously determined by the current that can be supplied to this capacitive load through the anode resistor of the pentode. With our choice of component values a rise time of 3 μ s was obtained. Since the fall time is dependent on the inner resistance of the conducting tube, this time is shorter in the present case.

5.9.4. Switching circuits

In the combined modulation mode grey shades are generated by the voltage mode method in the light density ranges while the PDM mode is used to obtain the higher densities. This can be achieved by a switching circuit operated by the video signal U_{in} from the preamplifier. This circuit switches the PDM mode circuit to the final amplifier if the density is higher than a certain density S_0 , while the voltage mode circuit is connected to that amplifier by the switching circuit if the density is lower than S_0 as indicated by the block diagram of Fig. 5:7. The diagram of this switching circuit is shown in Fig. 5:12.

FINAL AMPLIFIER

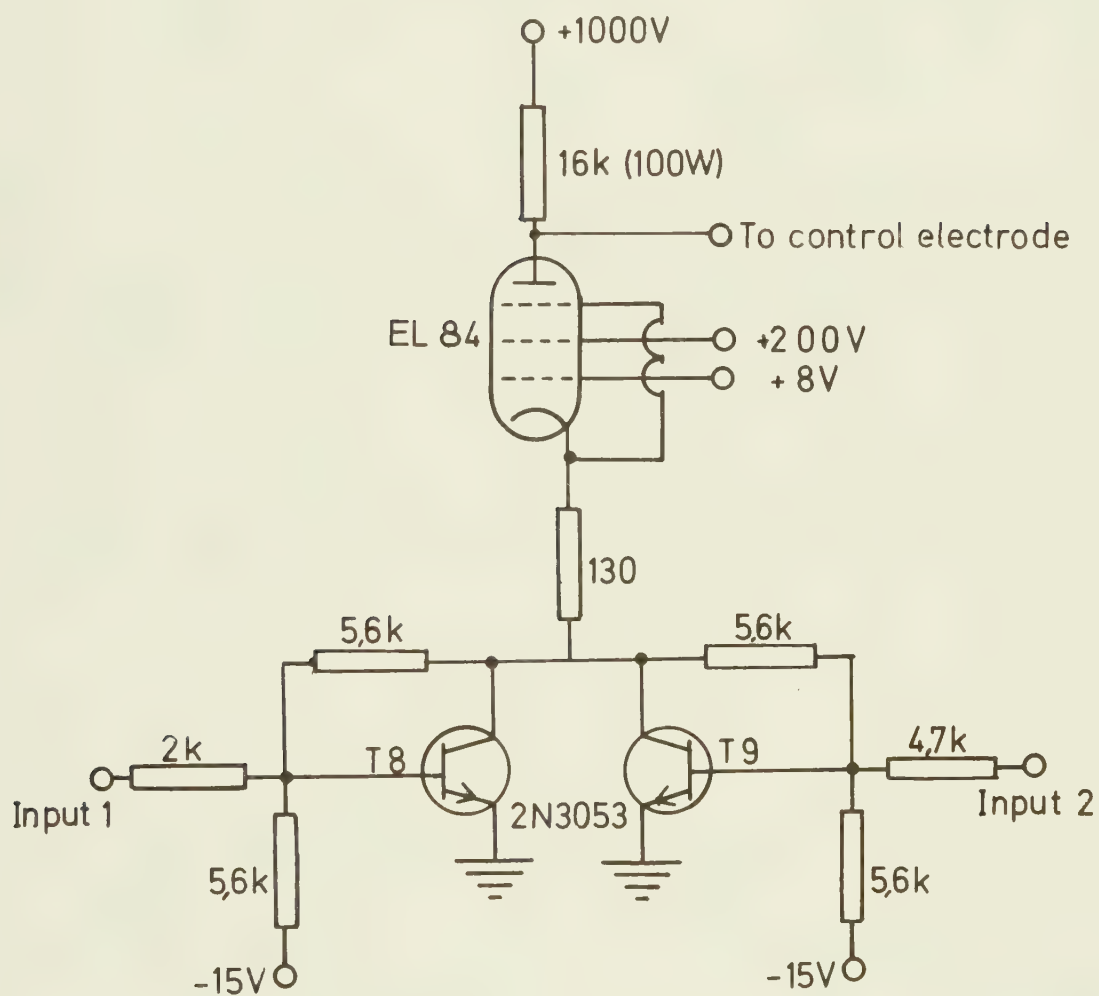


Fig. 5:11. Diagram of final amplifier.

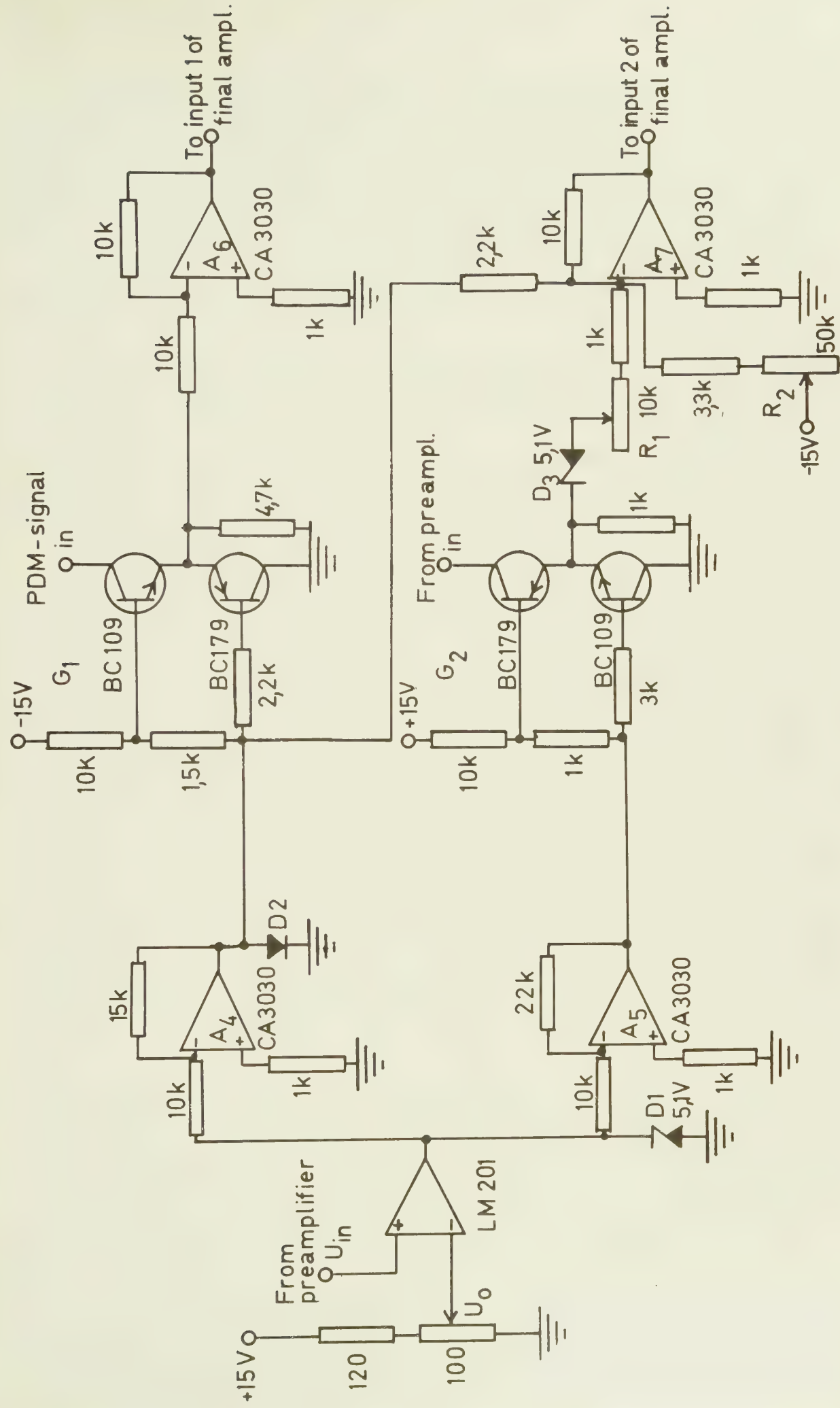


Fig. 5:12. Diagram of switching circuits.

The density value S_0 at which switching shall take place is determined by the voltage U_0 which is connected to the negative input of the voltage comparator LM201. Thus, because of the inversion of the video signal in the preamplifier, the switching circuit should work in the PDM mode if the video signal is lower than U_0 and in the voltage mode if it is higher than U_0 . This switching between the two modes of operation takes about 15 μ s with the circuit described below.

If the video signal U_{in} connected to the positive input of the comparator is lower than U_0 (PDM mode), the output voltage of LM201 is low but restricted to -0.6 V by the forward voltage drop in the silicon zenerdiode D_1 . After passing the inverting amplifier A_4 , the signal level is clamped to +0.6 V because of the silicon diode D_2 . This positive voltage opens the PDM gate G_1 by cutting off the pnp-transistor and opening the npn-transistor, thus allowing the PDM-signal to pass to the gate output. After inversion in the following operational amplifier stage the PDM signal is applied to input 1 of the final amplifier.

Since the output from the comparator is also connected to the inverting amplifier A_5 a voltage of +1.3 volts is generated at the output of A_5 , which opens the npn-transistor in the analog gate G_2 . The output of this gate is thus kept nearly at ground potential and no current can reach the input of amplifier A_7 because of the zener voltage of D_3 . Then the output of the amplifier A_7 is approximately at ground potential, which would drive the transistor T_9 in the final amplifier stage into cut-off (cf. Fig. 5:11). This is enhanced by a connection from the output of the amplifier A_4 to the input of amplifier A_7 , which drives the output of A_7 negative, if the circuit has been switched to the PDM mode. The transistor T_9 of the analog input 2 of the final amplifier is thereby cut off effectively.

If, on the other hand, the video signal voltage at the comparator input is higher than U_0 , the circuit should switch to the voltage mode of operation. In that case the output of A_4 is driven to -7.5 volts by the comparator. This is enough to make the pnp-transistor in the PDM-gate G_1 highly conductive, thus shortcircuiting the output to ground. This drives the voltage at the input 1 of the final amplifier to zero whereby the transistor T_8 is cut off.

In this position of the comparator the positive comparator output voltage also provides the necessary negative voltage to open gate G_2 after amplification and inversion in A_5 . Thus, the video signal from the preamp-

lifier is passed via the gate to the amplifier A_7 . A DC-voltage is subtracted from the signal by means of the zenerdiode D_3 before it is applied to the input of the amplifier A_7 . After suitable correction of the DC-level by means of the variable resistor R_2 and the gain by means of the resistor R_1 , the signal is inverted and connected to the input 2 of the final amplifier, thus providing an analog control of its output voltage as required for the voltage mode method.

5.10. Reflection density curve for the combination mode method

The density level, at which the switching between the two modulation methods takes place is determined by the limitations of the PDM mode method. As mentioned in chapter 2 the definite lower limit of the number of original drops in one pulse is about 5. In order not to approach this limit too closely, since that might cause interruptions in the recording trace pulse sequence, the switching takes place when approximately 7 - 9 original drops are let through. If the normal distance between the nozzle and the recording paper required for sufficient background suppression is used, all these drops have merged into one before they reach the paper since the front drop will be reached by the following drops in the same pulse (cf. Fig. 5:13). When this large drop hits the paper surface it spreads, covering a paper area which is larger than that given by the pulse duration ratio. The density will, therefore, be higher than determined by the on-off ratio of the PDM mode. Thus, the PDM mode does not produce that light grey shade which is theoretically expected. For this reason, the lower limit of the reflection density, where the switching to the voltage mode should take place, must be kept as high as 0.5 for a 10 μm nozzle. Since the reproducibility of the direct voltage method increases with decreasing density, it is desirable to lower this limit as far as possible.

The reflection density curve, obtained by the combination mode circuit and a 7 μm nozzle, is given in Fig. 5:14 where the density is plotted as a function of the input voltage U_{in} to the combined modulation mode circuit.

It has been mentioned earlier that the characteristics of the half tone reproduction should be chosen in such a way, that all grey shades are reproduced as true as possible throughout the entire density range. The most suitable shape of the density curve given in Fig. 5:14 may, therefore, be



Fig. 5:13. Drop trains of $7\ \mu\text{s}$ length have merged into single large drops 10 mm in front of a $10\ \mu\text{m}$ nozzle. Pulse repetition frequency 40 kHz.

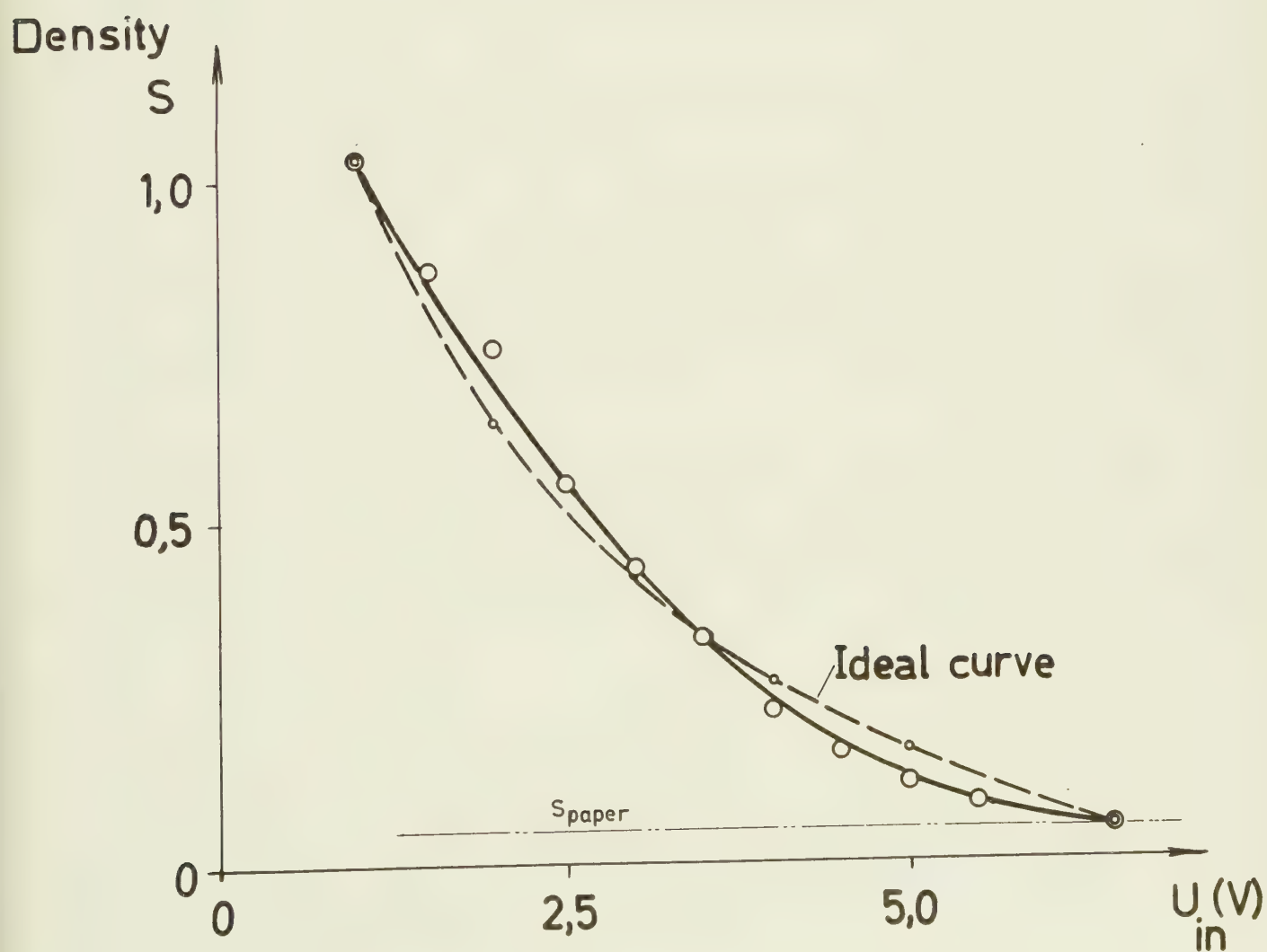


Fig. 5:14. Reflection density versus input voltage to the combination mode circuits.

deduced by the following considerations.

Since the output current from the photomultiplier is proportional to the reflectance R_o of the original image, the output voltage from the preamplifier which is equal to U_{in} is also proportional to R_o . Then, if the reflectance R_r of the reproduction is proportional to U_{in} , all the links in the transfer chain are linear and a correct half tone reproduction is obtained. Therefore, the reflectance R_r should be related to the input voltage U_{in} according to:

$$R_r = R_m + k_3 (U_{in} - U_m)$$

with $k_3 = \frac{R_p - R_m}{U_p - U_m}$

where (R_m, U_m) is the endpoint in the low reflectance range and (R_p, U_p) the endpoint in the high reflectance range. This relation represents a linear dependence for R_r versus U_{in} between these endpoints.

For the density S versus input voltage U_{in} the following relation is found for the ideal experimental case:

$$S = {}^{10}\log 1/R_r = {}^{10}\log \frac{1}{0.09 + 0.147 (U_{in} - 1.0)}$$

Here the endpoint values obtained from Fig. 5:14 have been used to adapt the ideal curve to the experimental one in such a way that the endpoints coincide. These values are $R_p = 0.90$, $R_m = 0.09$, $U_p = 5.5$ V and $U_{in} = 1.0$ V.

Fig. 5:14 shows that the combination mode circuit only approximately reproduces the ideal curve. The reason for this is that no correction of the video signal to obtain optimal grey scale characteristics has been made in the input amplifier of the present equipment. With such a correction the ideal curve could probably be reproduced with still higher accuracy.

As already mentioned, the density curve shown in Fig. 5:14 was obtained with a 7 μ m nozzle. This nozzle allows a higher drop formation frequency, thereby decreasing the graininess and the lower density limit for the PDM modulation, which in this case was about the density level 0.40. It also allows an increase in pulse repetition frequency from 10 kHz for the 10 μ m nozzle to 18 kHz for the 7 μ m nozzle.

By using a 10 μ m nozzle a similar coincidence of the experimental and theoretical density curves can be obtained. However, due to the lower drop

formation frequency the records show a much higher graininess even if the higher pulse repetition frequency is used (cf. chapter 7) for which reason only the curve obtained with the $7\mu\text{m}$ nozzle is given here. Further, a shorter control electrode than for a $10\mu\text{m}$ nozzle can be used as mentioned earlier, which also increases the quality of the record. The length of the control electrode in the present case was only 8 mm and thus the distance from nozzle to paper could be decreased to 10 mm.

This combination mode method as well as the pure PDM mode show a tendency to cause so-called "moiré"-patterns in areas of constant average density. This "moiré"-pattern is created by a certain disorder in the matrix pattern as soon as the PDM mode pulses are not exactly placed as shown in Fig. 5:1. The observed "moiré"-pattern is generated by an irregular positioning of the PDM pulses which, therefore, should be avoided. This can be achieved by triggering the circuit producing the linear ramp for the PDM electronics by a synchronizing signal from the drum rotation. In this way the exact position of each pulse on the recording paper can be controlled. To obtain the pulse pattern shown in Fig. 5:1, the synchronizing pulse should be advanced half a pulse period of the PDM pulse train for every second scanning line on the drum. Preliminary experiments have shown, that this procedure gave very satisfactory results. However, no further efforts were made in this direction since it was found that the "moiré"-patterns produced by a free running linear ramp generator do not deteriorate the quality of actual image reproductions seriously. Because of this no further attention is given here to methods which eliminate "moiré"-patterns in the reproductions.

A subjective estimation of the number of discernible grey shades obtained by the combined method has been made. According to this about ten grey shades might be distinguished from each other. This estimation is valid for larger areas while the number of discernible grey shades decreases with a decrease of the area due to the graininess, which will be evident from the determination of the granularity described below.

6. DETERMINATION OF THE DEFINITION OF THE METHOD

6.1. Introduction

For a reproduction process the ability to copy fine details without loss of definition as well as to give sharp outlines of the objects in the image are important properties. The subjective quality aspects associated with these properties are sharpness, resolution or resolving power and to a certain extent graininess. For the comparison of the ink jet method with other imaging processes it is of great importance to find measurable quantities which are good criteria of these subjective qualities.

Several papers have been published which deal with the measurement of these quality aspects of images, which are decisive for the perception of fine details in a photographic image. All the different methods proposed for this end search for physically measurable quantities, which correspond as nearly as possible to the subjective perception of the concept of definition or sharpness. Further, these qualities should preferably be chosen in such a way that they can be expressed by one parameter only.

In most of these methods, a test pattern with fine details is used, the spatial density distribution of which has been measured by means of a microdensitometer, whereafter the quality has been evaluated according to different principles. Thus, for many years the resolving power has been the accepted criterion of image quality. For the determination of resolving power a test pattern consisting of a large number of lines and spaces of equal width is used. By preparing a series of such patterns with increasing spatial frequency, the finest pattern in which the lines can still be resolved and counted is determined by examination under a microscope. The maximum number of lines per millimeter which could still be counted was then defined as the resolving power of the imaging process. Later it was found that this procedure lacked a good theoretical fundament, gave rise to certain ambiguousness and was not always reproducible. Further, the over-all resolving power of a complex system could not be correctly calculated from the resolving power of each separate link of the system. Because of this other methods have been introduced.

Higgins and Wolfe (1956) have, therefore, defined and measured the so called "acutance" and found an approximate correlation with this quality and the subjective concept of definition. The "acutance" is obtained by the photometric measurement of the spatial density distribution for a density-step by means of a long narrow slit. For the evaluation of the acutance a computation is required. Frieser and Biedermann (1963) measured instead the spatial density distribution for a printed line pattern by a microphotometer and plotted the contrast as a function of the spatial frequency for the line pattern. This procedure is very similar to the measurement of the modulation transfer function mentioned below. As the objective criterion on image quality the frequency for which the contrast had dropped to 50 % was chosen. Frieser and Biedermann could show that an increase of this frequency did coincide with an increase of the subjective perception of the sharpness of the image by a human observer for most kinds of images. A similar method was proposed by Ooue (1962) who found that the integral of the squared Modulation Transfer Function (MTF) over the spatial frequencies showed good correlation with the concept of definition. The modulation transfer function is obtained by the measurement of the spatial density distribution of an object with sinusoidal density distribution.

The final choice of test method for the present investigation of the definition obtainable by the ink jet device was determined by two requirements: first of all the production of high quality test patterns should be possible by a relatively simple method and secondly a rapid and reliable method for the evaluation of the test patterns seemed to be of large importance. The reproduction of high definition photographic test patterns by a photoelectric scanning procedure shown in Fig. 4:1 was excluded since the transfer characteristics of the scanning device would be added to the characteristics of the ink jet device. Instead the test pattern can be produced electronically by suitable pulses from a pulse generator synchronized to the rotation of the drum by trigger pulses from a photoelectric device relaying the position of the drum. A density step function for the measurement of "acutance" is easily generated in this way, however, test patterns having spatial periodicity are more convenient to evaluate in the density measurement. Such patterns can be made by means of the method described in section 6.3. and are easily obtained in the shape of either square-wave or sinusoidal density distributions. Therefore, this method was considered to be the proper choice for the present investigation. Since Langner et al. (1964) have shown that measurements from line patterns having a square-wave density distribution could be converted if necessary by Fourier analysis into results

obtained from a sinusoidal pattern, the line patterns produced by the ink jet device were produced with the square-wave technique. This procedure simplified the electronic circuitry required for the production of the signal voltage pulses.

In the following the definition has been determined both for the on-off modulation of the jet and for half tone modulation using the combined mode technique for the production of grey shades. The reason for this is that in many cases black-and-white images are to be reproduced which do not show any grey shades.

For the measurement of definition of half-tone images the modulation transfer function of the test pattern was determined as described among others by Molitz (1959). Here the signal transfer theory for linear systems as used in passive four terminal networks analysis in electrical engineering is applied to the photographic imaging process. This method cannot be used for the patterns produced with a pure on-off modulation of the jet, since the modulation transfer does occur via a nonlinear characteristic in this case. This is demonstrated by the curve for the voltage mode modulation shown in e.g. Fig. 5:3. In order always to be sure of a well collected jet in the "on"-state, the "on"-voltage must be chosen below the lower limiting voltage U_k for the spray formation. Thus the transfer curve is not linear in this case. Because of this the modulation transfer theory is not applicable for the on-off mode modulation, as the theory demands linearity of the characteristic transfer curve (cf. section 6.7.). Therefore, the resolving power defined above was used instead for the study of the on-off mode modulation and taken as the criterion of sharpness in that case.

6.2. Determination of the resolving power of the on-off modulation mode

In many cases originals to be copied by the ink jet process consist of black and white areas only, i.e. do not show grey shades. Typical examples of such black and white originals are weather charts and alphanumeric characters. When reproducing such images only a simple on-off modulation of the ink jet is required. In this case density levels between the extremes do not exist, because of which the resolving power as defined in the preceding chapter is a good criterion for the definition of the method. Further, the modulation transfer function of the ink jet device cannot be used for this determination since that method assumes a linear relationship between

density and the signal voltage applied to the control electrode as already mentioned above.

For the measurement of the resolving power test patterns were prepared as described in the following section. These test patterns were then measured in an apparatus described in section 6.4, while in 6.5. the results are presented.

6.3. Preparation of test patterns

For the determination of the resolving power a series of test patterns was required, each consisting of a number of parallel lines and spaces of equal width showing increasing spatial frequency from one pattern to the next. To avoid that the transfer function of the scanning device is included in the determination of the resolving power these patterns were not produced from a photographic original but by direct switching of the control voltage by a gated pulse generator, the pulses of which had rise and fall times of less than 1 μ s. This pulse generator was triggered from a photoelectric device G indicating the position of the drum which carried the recording paper as shown in Fig. 6:1. In this way parallel lines were created on the paper the direction of which was equal to that of the drum axis and thus perpendicular to the scanning lines. Since any other position of the lines relative to the scanning direction will result in a stronger dependence on the scanning line density, the test patterns used here will give a value of the resolving power most relevant for the ink jet modulation process.

Even in this investigation baryte paper was used because of its superior surface properties, while the surface speed of the drum and the scanning line density were chosen to match the nozzle diameters used for the production of the different test patterns. This choice was also determined by the different possible applications of the ink jet technique in which various nozzle sizes, drum speeds and scanning line densities are used. The parameters used in the different test patterns are shown in Table 6.1. In all experiments, the drop formation process was controlled by mechanical vibrations.

During the generation of the test patterns a trigger pulse is obtained from the electrooptical sensor G at a certain angular position of the drum each time the drum is rotated one turn. This pulse triggers the gated pulse

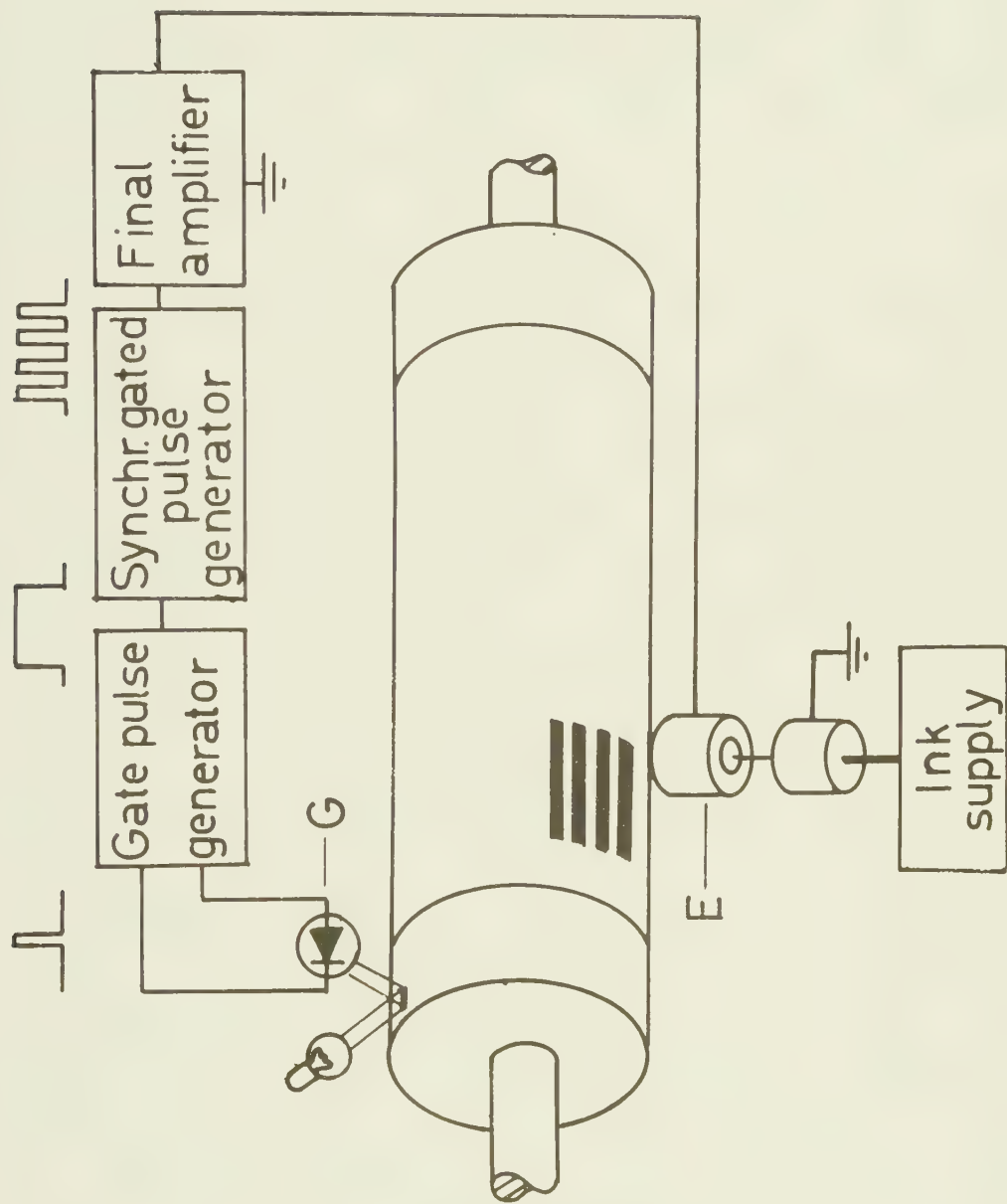


Fig. 6:1. Apparatus for the generation of test patterns.

Nozzle diameter (μm)	7	10	15	20
Control electrode length (mm)	8	10	14	20
"Off" control voltage (V)	800	1000	1200	1000
"On" control voltage (V)	30	30	30	30
Max. density S_{max}	1.10	1.43	0.80	0.50
Min. density S_{min}	0.05	0.08	0.08	0.06
Mechanical vibration frequency (MHz)	1.25	1.03	0.75	0.57
Drum surface speed (m/s)	3.0	3.0	16.0	8.0
Recording line density (lines/mm)	10	10	7	4
$v_f = 0.5$ (lines/mm)	5.5	4.8	2.4	4.0
Resolving power $v_f = 0.1$ (lines/mm)	7.3	6.5	3.2	5.0

Table 6.1.

generator producing the signal pulses for the ink jet control. At the start of the gate pulse the pulse generator generates a pulse train, the total duration of which was determined by the length of the gate pulse. After amplification in the final amplifier these pulses control the on-off intensity modulation of the ink jet. Since the pulse train is repeated identically for every turn of the drum, a line pattern is generated perpendicular to the recording direction, the spatial frequency of which can easily be varied by varying the frequency of the pulse generator. This pattern constitutes the required test pattern for the determination of the resolving power.

The electrooptical triggering device introduces a certain uncertainty in the starting time of the pulse train. This uncertainty was found to be $2 \mu\text{s}$ at a maximum and corresponds to a maximum displacement between successive recorded pulses of 0.006 mm at the paper speed of 3 m/s . From the results presented below it will become evident, that this uncertainty is negligible in the present investigations even at the highest spatial frequencies which could still be resolved.

Test patterns were produced in this way using nozzle diameters of $7, 10, 15$ and $20 \mu\text{m}$. The other parameters used in connection with the different diameters are shown in Table 6.1.

6.4. Experimental determination of the resolving power

The test patterns generated in this way may then be examined visually with the aid of a microscope of suitable magnification. In this way the highest spatial frequency for which alternate lines still can be discerned can be determined which would give the resolving power of the method. Alternatively, a microdensitometer can be used which procedure would be less liable to subjective errors. Since the investigation of the modulation transfer function described in section 6.9. required a microdensitometer for the measurement of reflectance variations anyway, this instrument was also used in the present case because of its higher reliability.

The construction of the microdensitometer is shown schematically in Fig. 6:2. The test pattern was fixed to a drum with the lines carefully adjusted to be parallel with the axis of the drum. The drum was rotated very slowly with a surface speed of only 0.33 mm/s , thereby causing the test pattern to pass the object plane of the optics of the stationary microdensi-

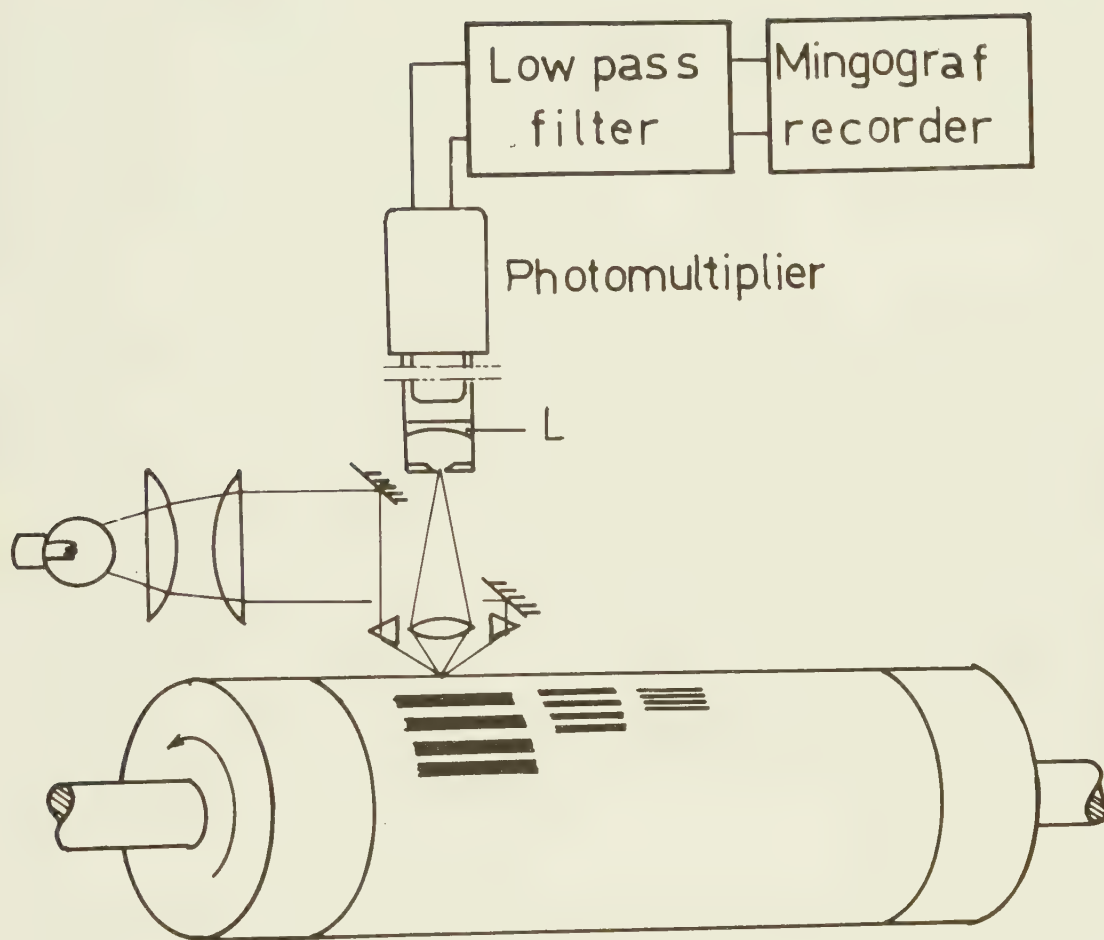


Fig. 6:2. Microdensitometer for the determination of the resolving power and the modulation transfer function.

tometer. This consisted of a Leitz microscope objective including the illumination device "Ultropak" having an objective magnification of 11x. In fact, the optical system used here is the same as that employed in the scanning device described in section 4.2. The optical system produced an image of the line pattern on the drum with a linear magnification of 3 times a few centimeters behind the microscope objective, where a 1.5 mm long and 0.03 mm wide slit was placed. The slit was carefully aligned with the axis of the drum and thus also with the line patterns. Thus, this slit defines the area of measurement of the microdensitometer. To decrease the influence of scattered light from the interior walls of the microscope objective a diaphragm was inserted between the objective and the slit and its walls were carefully blackened.

The intensity of the light reflected from the test pattern through the slit was measured by means of a photomultiplier (Philips XP 1110). In order to increase the effective area of the photosensitive cathode utilized for detection of the reflected light, a concave lens L was inserted between the slit and the photomultiplier. The anode current of the photomultiplier is then proportional to the reflectance of the image element under study, the factor of proportionality being dependent on the light intensity delivered by the illumination device as well as the amplification in the photomultiplier. Since both of these parameters are very dependent on the supply voltage, highly stabilized voltage supplies were used as power sources throughout the measurements.

The anode current obtained in this way from the photomultiplier is proportional to the reflectance density of the test pattern under study. This current was then amplified and applied to a low pass filter to decrease the noise in the photomultiplier signal. After the filter the signal was recorded by a Mingograph recorder. The high upper frequency limit of this recorder assured the fidelity of the record in spite of the relatively high speed of 0.33 mm/s at which the surface of the drum was moving under the microscope objective. This speed of rotation was chosen for practical reasons.

In the actual measurement, the test pattern was fastened to the drum as described above and the drum rotated slowly by a motor. The spatial reflectance distribution of the test pattern was then measured by the reflection microdensitometer and recorded on the Mingograph recorder. The results obtained in this way are presented in the next section.

6.5. Results

The resolving power of an imaging device is normally given only by stating the number of lines per millimeter which actually can be resolved by a suitable method. Since the ink jet device studied here differs in many respects from other imaging devices, i.e. the photographic process, the information about the definition of black and white images obtained with that device may be improved by not only stating the resolving power measured but also by introducing the function $f(\nu)$. This function is defined by the equation

$$f(\nu) = \frac{R_{\max}(\nu) - R_{\min}(\nu)}{R_{\max}(0) - R_{\min}(0)}$$

where $R_{\max}(\nu)$ and $R_{\min}(\nu)$ are the maximum resp. minimum reflectances as measured by the microdensitometer on a test pattern with a spatial frequency ν while $R_{\max}(0)$ and $R_{\min}(0)$ are the same magnitudes measured at zero spatial frequency. The denominator in the above equation is only introduced for normalization purposes. The function $f(\nu)$ actually obtained in the four cases given in Table 6.1 is presented in the Figures 6:3 through 6:6.

The spatial frequencies for which $f(\nu)$ has dropped 50 % and 90 % respectively are given in Table 6.1. Since the 90 %-values seem to coincide with the visually obtained values of the maximum spatial frequency, for which the lines may be counted with certainty, these values have been stated as the resolving power. The 50 %-values are presented partly in order to give a rough idea of the rate of decrease of $f(\nu)$ with spatial frequency, and partly to facilitate the comparison of the resolving power of the on-off mode modulation made with the modulation transfer function of the half tone reproduction achieved with the ink jet device studied below.

The results presented in Table 6.1 were obtained from test patterns, all of which were produced by ink jets using controlled drop formation by mechanical vibrations. Because of this it should be pointed out that a removal of the mechanical vibrations decreases the resolving power for all nozzle diameters except for the 7 μm nozzle. For this nozzle the resolving power is approximately unaltered. The reason for this is probably that due to the very short distance between the nozzle and the recording paper used with the 7 μm nozzle and to the high resolution obtained in this case, other factors than the uniformity and the number of drops in the drop trains limit the resolving power. One of these is probably the finite size of the dots

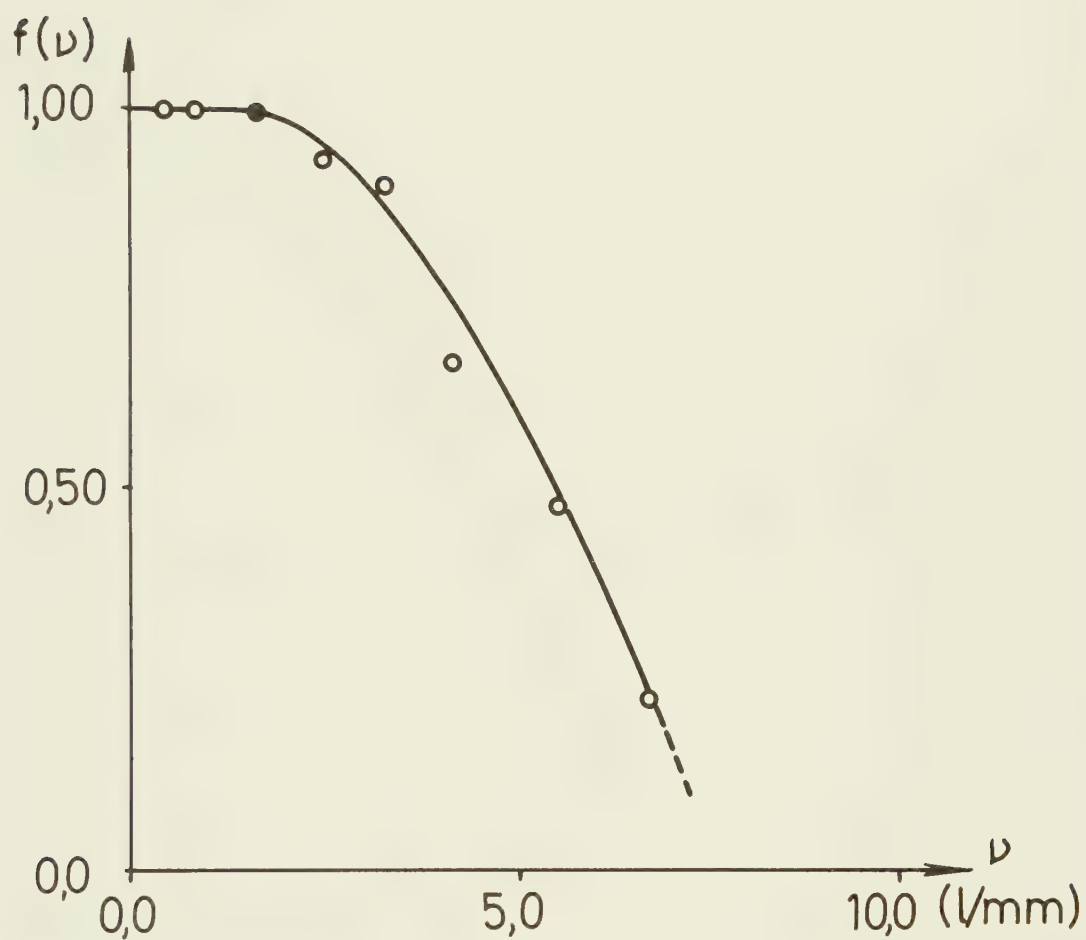


Fig. 6:3. $f(v)$ used for objective determination of the resolving power of a 7 μm jet with controlled drop formation.

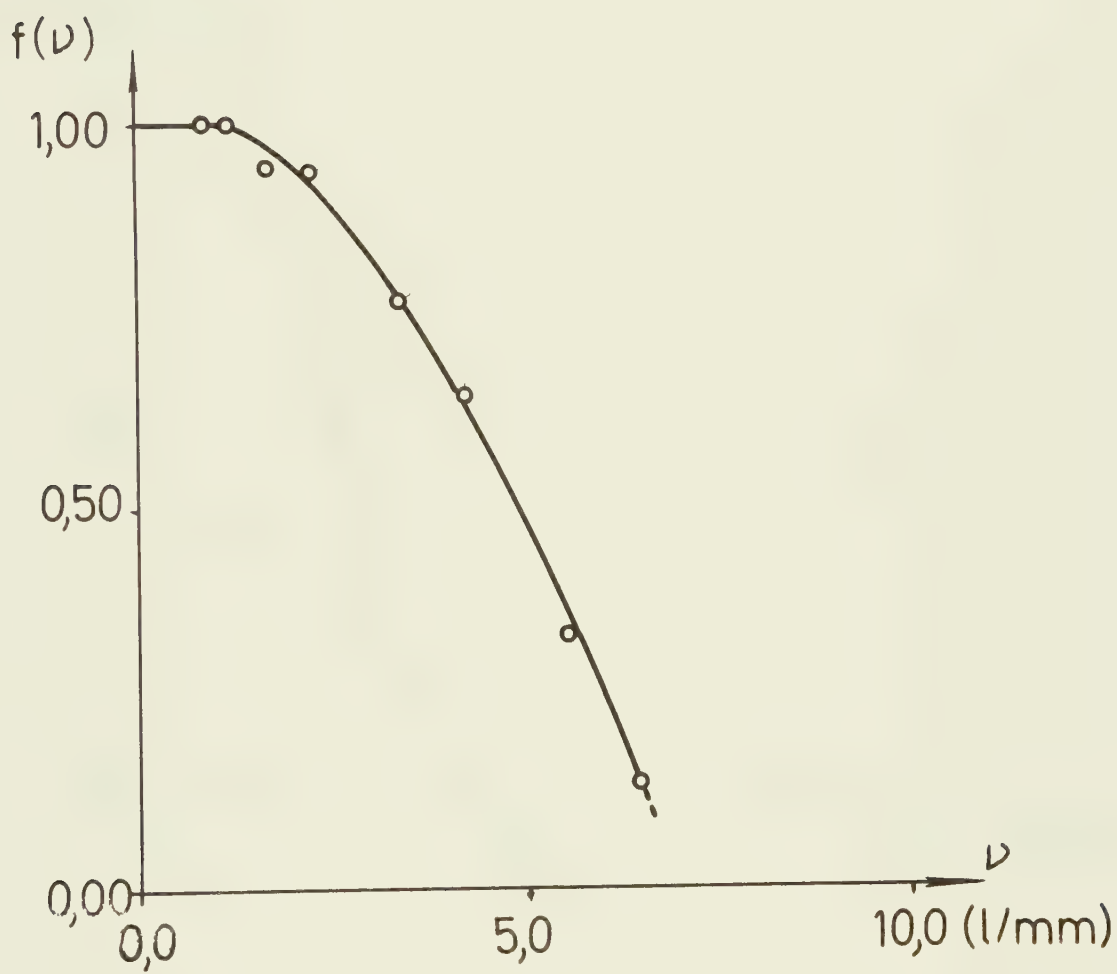


Fig. 6:4. $f(\nu)$ used for objective determination of the resolving power of a $10\text{ }\mu\text{m}$ jet with controlled drop formation.

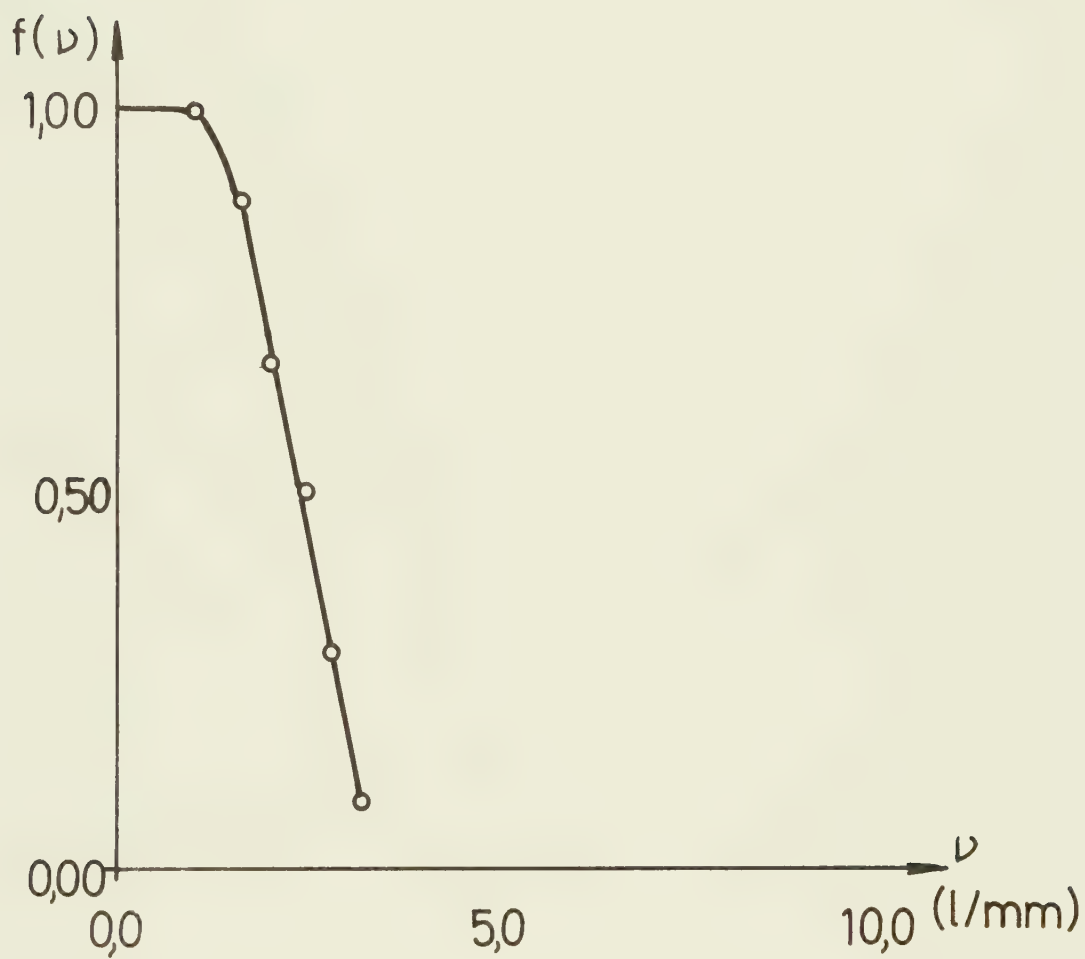


Fig. 6:5. $f(v)$ used for objective determination of the resolving power of a 15 μm jet with controlled drop formation.

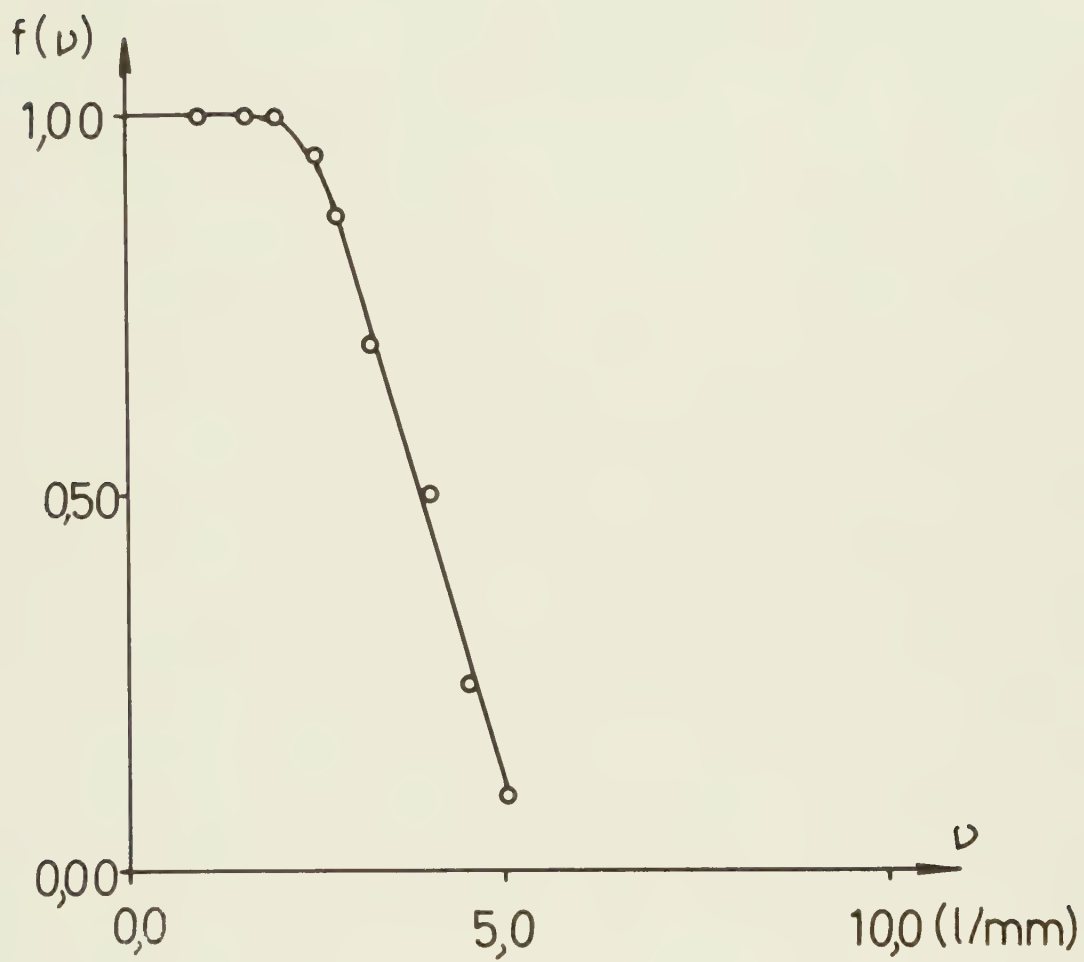


Fig. 6:6. $f(v)$ used for objective determination of the resolving power of a 20 μm jet with controlled drop formation.

created by the minimum pulse drop trains. Other factors may be air currents in the control electrode, irregularities of the surface of the recording paper etc.

A comparison of the values of the resolving power found for the 15 and 20 μm nozzles leads to a somewhat unexpected result. According to Table 6.1 the resolving power for the 20 μm nozzle is larger than for the 15 μm nozzle. The reason for this, however, is the very different parameters chosen in the two experiments. This choice was motivated by certain possible applications in mind, which required that an A4 sized black and white original can be copied by the ink jet device in 30 seconds. This can be achieved either with a high surface speed of the recording paper together with a reasonably high scanning line density or with a lower surface speed and a lower line density. The first combination was tested with a 15 μm nozzle since here a higher upper frequency limit is required because of the high surface speed of the recording paper, while for the second combination a larger nozzle was used. From Table 6.1 it can be seen that the combination of nozzle diameter and paper surface speed is of large importance for the resolving power since the highest resolving power was obtained for the 20 μm nozzle in the low speed combination. On the other hand two obvious disadvantages are found with the low speed method which also is demonstrated in Table 6.1. The maximum density is low since the low line density leaves white spaces between adjacent recording lines, thus decreasing the contrast of the recorded image. The other disadvantage is the low resolving power in the direction perpendicular to the scanning direction which is seriously limited by the low scanning line density of only 4 lines per millimeter. Since in most applications the resolving power of the process should be equally good in all directions, the scanning line density should at least be two times as large as the resolving power, which is not the case in the 20 μm nozzle experiment.

The results presented seem perhaps to favour the 15 μm nozzle in combination with a high surface speed. However, it should be pointed out that the high surface speed does introduce other problems. First of all the centrifugal forces on the surface of the drum become quite large if a drum large enough to carry an A4-sized paper is used. Because of the high speed of rotation this drum has also to be balanced carefully. Finally, since the surface velocity is very high, air currents are generated between the drum and the control electrode which are strong enough to disturb the jet on its way from the small aperture in the control electrode to the recording paper.

The validity of the results given in Table 6.1 can be checked in the following way. In Fig. 6:7 a high quality test pattern series produced by a printing process is shown in natural size. The numbers assigned to each pattern show the number of lines per millimeter displayed by the pattern. Below a blow-up of that part of the original is shown which contains the patterns with high line densities.

Reproductions of these test patterns were made using the twin-drum apparatus shown in Fig. 4:1. Surface velocity and scanning line density were 3 m/s and 10 lines per millimeter. A 7 μm nozzle was used together with control of the drop formation process and all other parameters were the same as those given for the 7 μm nozzle in Table 6.1, because of which the reproductions obtained in this way should be roughly comparable with the value of the resolving power determined by the microdensitometer technique above.

Fig. 6:8 shows a reproduction of the test pattern series obtained in this way. Again the appearance of the reproduction in its original size as well as a blow-up of the high line density part is shown. From this we find by visual inspection that the horizontal part of the test pattern showing 7.1 lines per millimeter still can be distinguished well enough to allow the counting of the lines, which is in good agreement with the resolving power of 7.3 lines per millimeter given in Table 6.1. However, the vertical lines of this test pattern are not reproduced as well. This is due to the fact that the direction of these lines is parallel to the scanning direction used in the reproduction process. Since the scanning line density was only 10 lines per millimeter, it is impossible to reproduce patterns having a higher line density than 5 lines per millimeter. This fact is also demonstrated by the reproduced test patterns shown in Fig. 6:8.

6.6. Determination of the modulation transfer function of grey scale patterns

The analysis of the quality aspect of definition and sharpness of half tone images obtained with the ink jet device will be performed in a somewhat different way than the measurement of the resolving power used in connection with the study of pure black and white images. The reason for this is that better methods have been developed for images containing shades of grey as described by Perrin (1960) and Langner (1963).

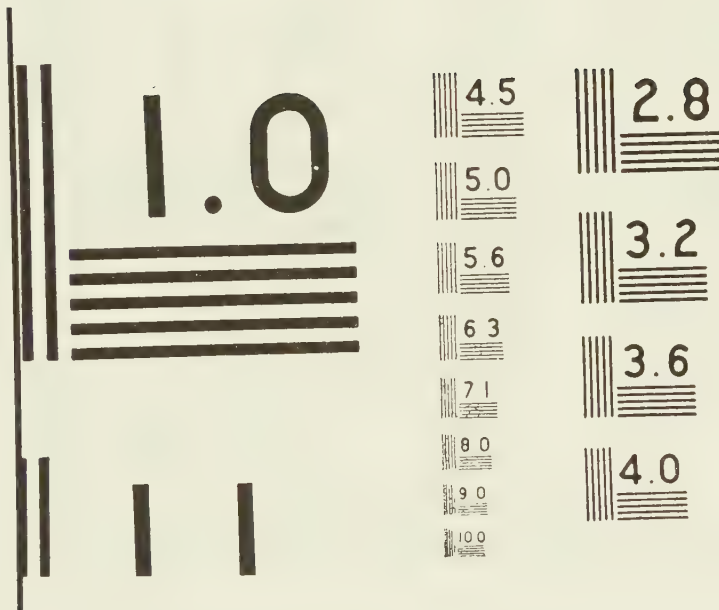
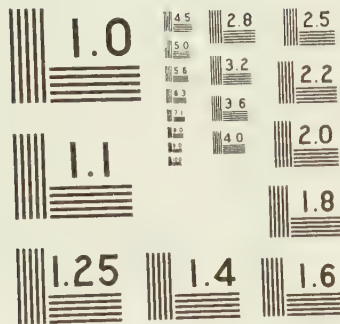


Fig. 6:7. High quality test pattern for resolving power studies in natural size (above) and enlarged (below). The figures show the lines per millimeter of each particular pattern.

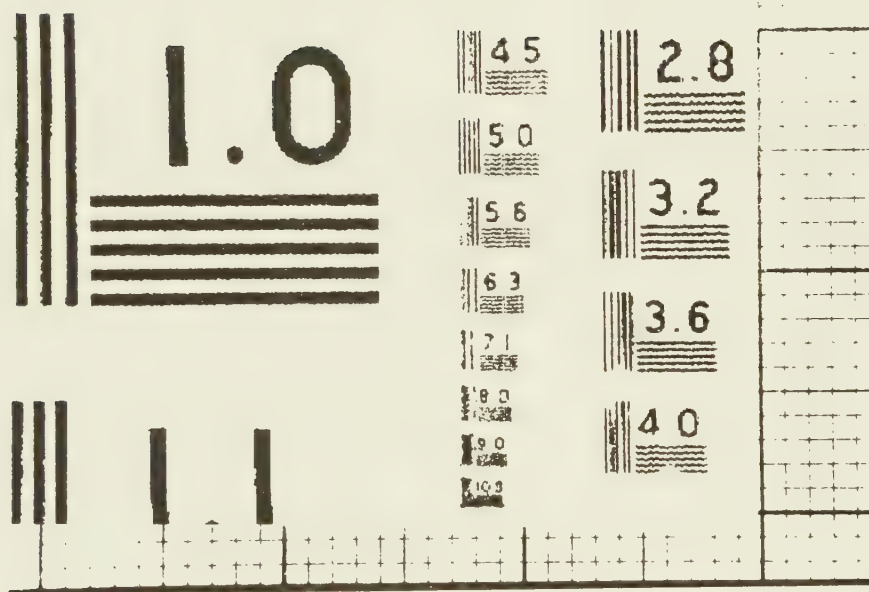
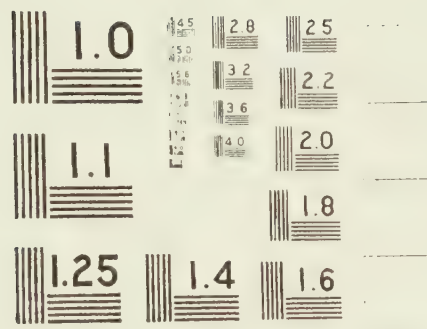


Fig. 6:8. Reproduction of test pattern shown in Fig. 6:7. Natural size above and enlarged below. Millimeter scale given for comparison.

It has been mentioned earlier that any method useful for the measurement of image quality should define this value preferably by only a single figure, the magnitude of which should agree as well as possible with the subjective impression of this quality assessed by the human eye. This requirement is adequately fulfilled by the measurement of the resolving power used above. However, when complex systems consisting of several links are used for image handling, it would be very convenient to be able to calculate the image reproducing quality of the entire system from the same quantity of each separate link. Since the resolving power did not lend itself easily to such calculations and did not give satisfactory results in all applications, the modulation transfer function (MTF) came generally into use (cf. e.g. Perrin 1960). However, it is a prerequisite for the applicability of the MTF method for the measurement of image quality that the image reproducing device is linear, i.e. that the reflectance or light intensity of each element of the original is reproduced proportional into the corresponding element of the image. Because of this the MTF could not be used in the previous sections.

In the following sections the imaging properties of the reproduction system used in chapter 8 shall be studied. Since the only new element in this system is the ink jet device in conjunction with the combination mode electronics, only this part of the system will be examined. It will be shown below that this part of the system transfers reflectance variations in a roughly linear way because of which the quality of the half tone images obtained with the ink jet device in chapter 8 can be studied by the measurement of the modulation transfer function as proposed by Molitz (1959). In the following, the fundamentals of this method as well as its modification to fit the present problem will be discussed.

6.7. The MTF method and its application to ink jet images

As was pointed out by Langner (1963) a linear imaging system is characterized by its modulation transfer function (MTF) which is only dependent on the spatial frequency. Further, the MTF of any number of linear links which are successively effective on the signal, is equal to the product of the individual transfer functions. Hence the determination of the MTF for each link is an appropriate means for the analysis of a compound system consisting of several links.

For the measurement of the MTF line patterns very similar to those used for the determination of the resolution power should be produced. However, according to the fundamental theory (e.g. Molitz 1959) the density of these patterns should vary in a sinusoidal way and not discontinuously as was the case in the line patterns used previously. As before, the line patterns should have different spatial frequencies, some of which lie well above the resolving power of the device under investigation.

The reflectance R of these line patterns is then measured with a microdensitometer in a way very similar to that described in section 6.4. The output signal from the microdensitometer which is proportional to the reflectance of the sample is then recorded continuously by a strip chart recorder. From this record the maximum reflectance $R_{\max}$ and minimum reflectance $R_{\min}$ can easily be obtained and the reflectance modulation $M_R(\nu)$ computed from the equation:

$$M_R(\nu) = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}}$$

for each line pattern with the spatial frequency ν . Because of the limited resolution of all image producing devices, the value obtained for $M_R(\nu)$ will be reasonably constant for low spatial frequencies while it decreases at spatial frequencies in the vicinity of the resolving power of the device. For even higher spatial frequencies, $M_R(\nu)$ will drop to zero for obvious reasons. It might be of interest to point out that $M_R(\nu)$ is identical to the contrast of line patterns, which was used by Frieser and Biedermann (1963) to obtain a single quality figure, which was in good accordance with the subjective impression.

To obtain the modulation transfer function $m(\nu)$ from $M_R(\nu)$ we have to normalize the measurements from our microdensitometer. This can easily be obtained by dividing the $M_R(\nu)$ determined at the spatial frequency ν of the line pattern by $M_R(0)$ which is the reflectance modulation obtained at zero spatial frequency. In practice this value can be obtained from measurements on line patterns with very low spatial frequencies. The modulation transfer function is then given by

$$m(\nu) = \frac{M_R(\nu)}{M_R(0)}$$

It is clear from this expression that the MTF is dependent on the spatial frequency and equal to one at very low values of ν .

It was pointed out before that it is very desirable to define the quality of a certain image by a single figure which adequately corresponds to the subjective appraisal of image quality made by the human eye. It has been shown (Frieser and Biedermann 1963) that the spatial frequency at which the contrast for square wave line patterns has dropped to 0.5, that is to 50 % of its highest value, can be used as such a measure. Because of this the quality of the ink jet patterns investigated in the following is stated by giving the spatial frequency ν_{50} at which the MTF has dropped to 50 %.

In chapter 5 it is shown, that grey shades can be produced by the ink jet in two different ways, the voltage mode method and the PDM mode method. Further it was found that both methods had certain disadvantages which could be avoided by using both methods simultaneously in such a way that the light grey shades were generated by the voltage mode method while for the dark shades the PDM mode method was used. Since this combination mode method should preferably always be used if high quality images containing grey shades are to be obtained all the line patterns investigated by the MTF method were produced with this method.

Before using the MTF for quality studies of images produced by the combination mode method, it has to be shown that this device really has a linear characteristic as required by the theory for the MTF method. That this is really the case can be proved by plotting the reflectance instead of the reflection density as a function of the input voltage to the combination mode electronics as was done earlier in Fig. 5:14. This dependence is plotted in Fig. 6:9 which shows that the reflectance is roughly a linear function of input voltage if the highest reflectance range is disregarded. Although the linearity is not quite perfect we do not think that this introduces errors into the determination of the ν_{50} value of such a magnitude that the MTF method cannot be used for quality determinations of images produced by the ink jet.

When producing line patterns of different spatial frequencies with the ink jet device for the appraisal of its capabilities, it is of importance that only the MTF of the device alone (including the combination mode electronics) is measured. Therefore, the reproduction apparatus used for the generation of the images described in chapter 4 was not used, since the MTF of the optical scanning device as well as the preamplifier electronics would be included in the measurements. To avoid this, the line patterns were generated by a gated pulse generator as described below. Each pulse sequence from

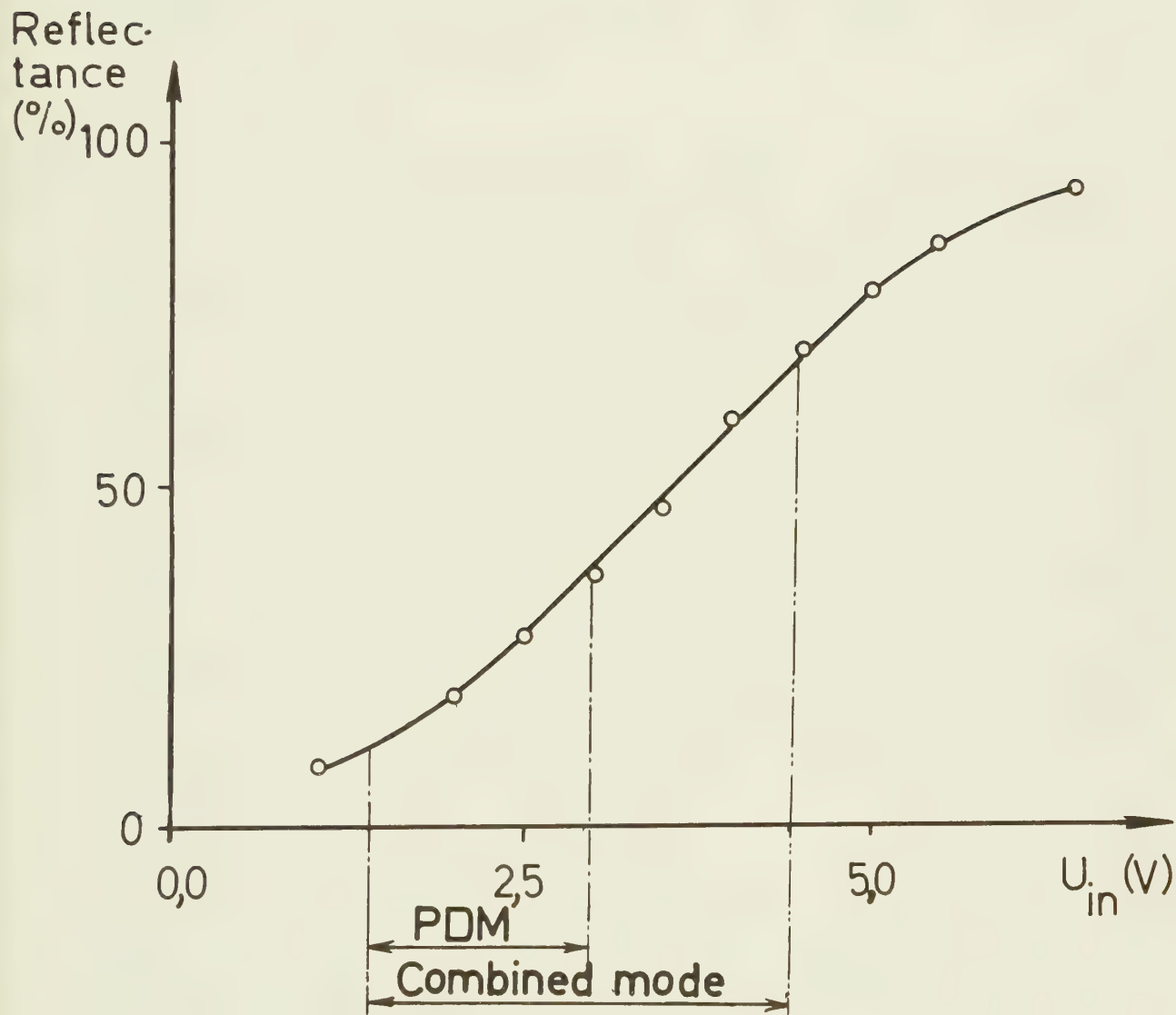


Fig. 6:9. Reflectance created by the combination mode method as a function of the input voltage to the electronic circuits. The arrows indicate the modulation ranges used for the MTF-determinations.

this generator has to be triggered from the photoelectric device indicating the drum position. This triggering requires a high degree of accuracy to avoid flutter of the pulses which would decrease the v_{50} value. This requirement could be met readily when square wave pulses were supplied by the pulse generator which is clear from the results obtained for the on-off modulation of the jet investigated in the earlier sections of this chapter, while sine wave trains could not be generated with equal phase accuracy with the present equipment. Because of this the line patterns used for the determination of the MTF for the combination mode method were made using square wave pulses as the signal voltage.

It was mentioned earlier that the fundamental theory of the MTF method requires a line test pattern the reflectance of which varies in a sinusoidal fashion. However, in principle, any input signal with a known spatial frequency spectrum can be used for measuring the MTF by means of Fourier analysis (Molitz 1959). Using this fact, Langner and Müller (1963) showed that for a square wave pattern of spatial frequencies in the vicinity of the cut-off frequency for the MTF the square wave distribution of reflectance is approximately transformed into a sinusoidal distribution. The amplitude of this sinusoidal distribution is approximately $4/\pi$ times the amplitude of the square wave distribution. In their experimental investigation they studied the differences in the modulation transfer function between a sine wave pattern and a square wave pattern without applying harmonic analysis to the square wave measurements. In this way they found that the square wave patterns gave approximately 20 % higher values for the MTF at higher spatial frequencies. However, the value v_{50} for which the MTF had dropped 50 % was only about 10 % higher for the square wave distribution.

From these results we can conclude that an investigation using a square wave distribution generally gives an MTF which is a little too "good". Thus, in spite of the fact that the use of patterns with sinusoidal reflectance distribution is the fundamental method used for the determination of the MTF, square wave patterns can also be used as long as the demands on the accuracy of the method are not too high. Since the present investigation is only meant to be a general survey of the capabilities of the ink jet device and since it was difficult to exclude errors due to inadequate triggering of the sine wave train mentioned above, it was considered appropriate for this first study of the MTF of the ink jet device to measure the MTF of square wave distribution patterns and present the results without any subsequent harmonic analysis. However, it should be pointed out once more that the MTF

obtained in this way promises a slightly better image quality than is actually obtained by the ink jet device.

For comparison the MTF of certain photographic material was also determined.

6.8. Preparation of test patterns

When preparing test patterns for the determination of the MTF of photographic material the following requirements are usually met.

a. The modulation M_R should be restricted to a linear part of the characteristic curve of the photographic material.

b. The modulation should lie in a range which is relevant for the images produced using this material.

For the ink jet device using the combination mode electronics, the most linear part of the characteristic curve in Fig. 6:9 extends around the 50 % point of reflectance. On the other hand, an estimation of the relevant range for the picture production shows that also the lowest reflectance values should be considered. When making the choice between lowest possible distortion and better relevance the last factor was considered to be most important.

As described above, variations of the reflectance are obtained by the PDM mode method for the lowest reflectance values while the voltage mode is used for higher values. Because of this fact different results may be obtained for the MTF of the ink jet device if the switching between the two modes occurs in the modulation range or not. Thus it was considered desirable to make separate test patterns for the two cases. Therefore, for the relevant reflectance range, one set of test patterns was made with a modulation that included the switching point (cf. Fig. 6:9) and another set in which the modulation was restricted to the range, where only the PDM mode method was used. The two modulation ranges actually used for the production of these test patterns are indicated in Fig. 6:9 by the two arrows parallel to the abscissa, while the corresponding density values are given in Table 6.2.

Now, accepting that test patterns with a square wave distribution of reflectance can be used instead of the sinusoidal distribution, the test pat-

terns can be made in the same way as the patterns used in the resolving power determinations. The method for this was already shown in Fig. 6:1. The only difference here is that the combination mode electronics were used instead of the final amplifier only. Square wave pulses of suitable amplitude to generate the grey scale modulation range indicated in Fig. 6:9 were then applied to the input of the combination mode electronics.

In order to correlate these measurements to the reflection density curve for the combination mode method shown in Fig. 5:14 the reflection density of the test patterns produced in this way should be determined. To this end, a test pattern having a spatial frequency of nearly zero was created by the same signal voltage values as were used to produce the real test patterns. The large light and dark areas of this special pattern were then measured in the reflection densitometer used earlier for the measurement of grey scales. The results of these measurements are given in Table 6.2 together with other parameters of interest.

6.9. Measurement of the modulation transfer function

It has already been mentioned that the MTF of the different test patterns was determined by measuring the reflectance variations with the microdensitometer described in section 6.4. Even in this case the drum carrying the test pattern was rotated slowly by a motor and the output signal from the microdensitometer recorded simultaneously on a strip recorder.

Due to the finite resolution of the microdensitometer, this arrangement does not provide a perfect measurement of test patterns having higher spatial frequencies. Therefore, the MTF measured in this way must be corrected for the modulation transfer function $m_m(\nu)$ of the microdensitometer itself. To this end the MTF $m_m(\nu)$ had to be determined by using high quality printed test patterns as shown in Fig. 6:7. These patterns consisted of lines with a maximum spatial frequency of 10 lines/mm. The result of these measurements is plotted in Fig. 6:10 which shows that the MTF of the microdensitometer decreases for spatial frequencies larger than 5 lines/mm. Thus, any results obtained with this microdensitometer at spatial frequencies higher than 5 lines/mm have to be corrected for the MTF of the microdensitometer.

According to transfer theory (cf. e.g. Molitz 1959) the actually measured modulation transfer function $m_r(\nu)$ is the product of the MTF of the test

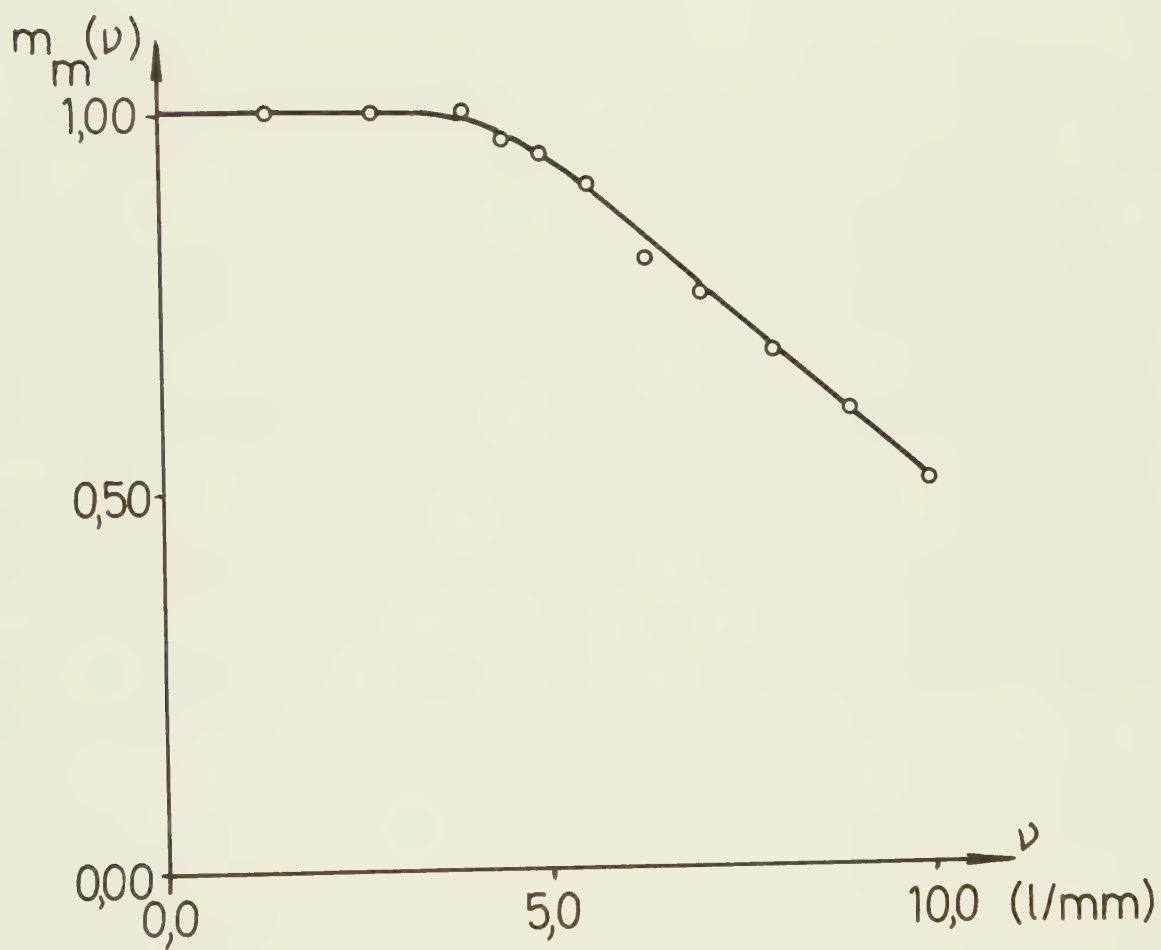


Fig. 6:10. Modulation transfer function of the microdensitometer.

pattern $m(v)$ and the MTF of the microdensitometer $m_m(v)$. Thus $m(v)$ of the process under investigation can be obtained from

$$m(v) = \frac{m_r(v)}{m_m(v)}$$

Again this relation is correct only for a sinusoidal reflectance distribution. Since the $m_m(v)$ values are approximately 1 for the spatial frequency range of interest for the ink jet modulation process, the use of a square wave distribution in the measurement of both $m_m(v)$ and $m_r(v)$ only introduces a second order correction which is neglected in the present investigation.

In order to test the reliability of the method for the determination of the MTF described here, an object with a known modulation transfer function was measured. For this end test patterns were created on photosensitive paper of which the MTF was known (Agfa Brovira Normal, Biedermann 1967). To create a suitable test pattern on this paper, a high quality line pattern of increasing spatial frequencies produced on a high resolution photographic emulsion was contact copied onto the paper. The original test pattern had a square wave density distribution. The MTF of this paper as measured by the microdensitometer and corrected for $m_m(v)$ is shown in Fig. 6:11. For comparison the corresponding curve presented by Biedermann (1967) is also given. The differences between the curves are small and are probably due to the utilization of a somewhat different density range and differences in measurement techniques. However, this result seems to indicate that the measuring technique for the MTF used here can be accepted for the present purpose.

6.10. Results

A typical recording obtained from the measurement of the reflectance of an ink jet test pattern by the microdensitometer is shown in Fig. 6:12. The square wave distribution of the line pattern is clearly distinguishable, however, a certain amount of noise is superimposed on the curve. This noise is due to stochastic variations of the reflection density and, in those parts of the pattern which were created by the PDM mode method, also by the variation in the PDM pattern.

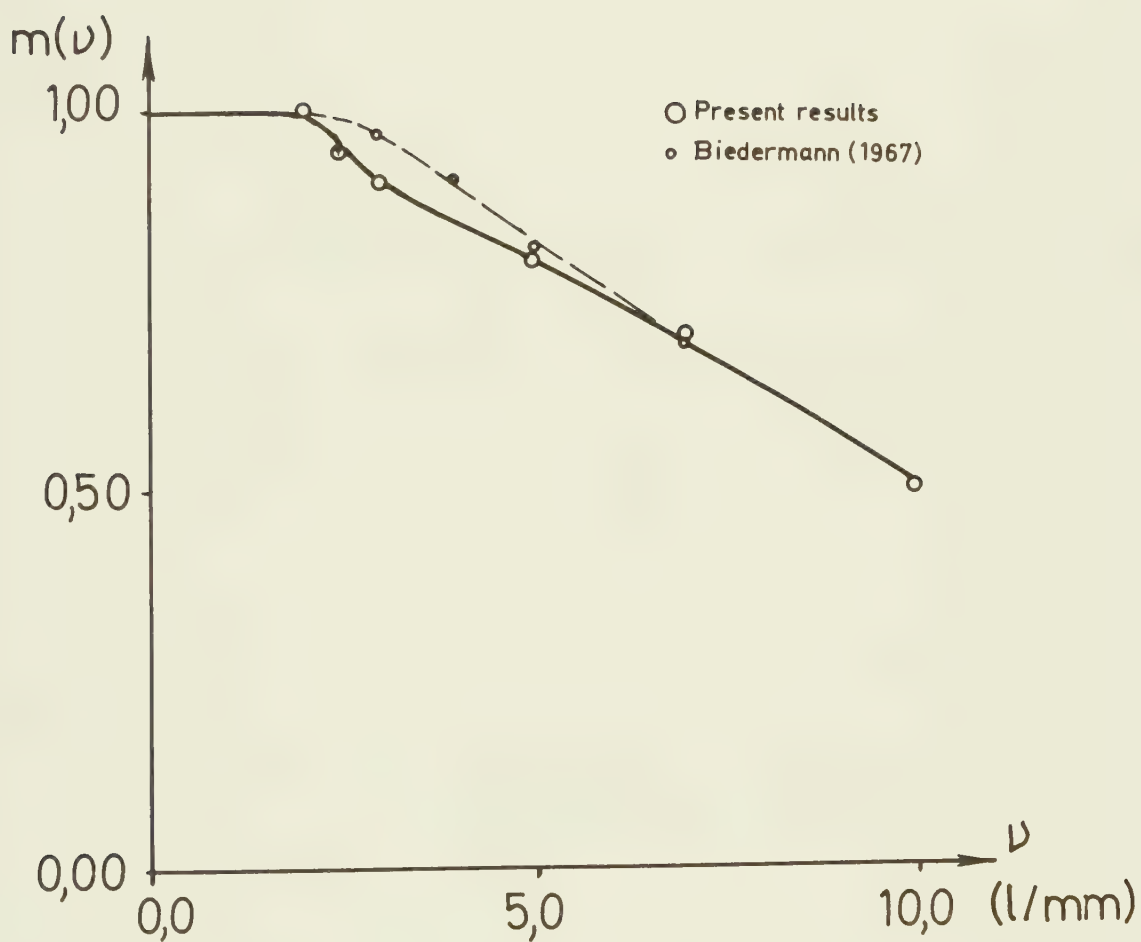


Fig. 6:11. Modulation transfer function for light sensitive paper (Agfa Brovira Normal). Dashed line shows where measurements by Biedermann (1967) differ from present measurements.

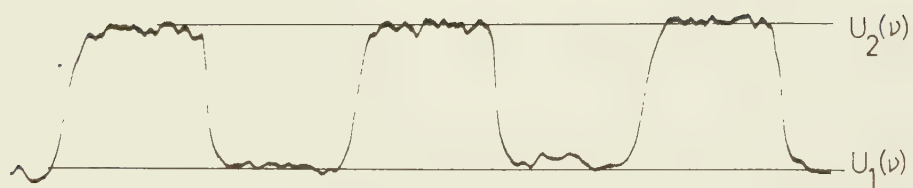


Fig. 6:12. Record obtained from microdensitometer measuring an ink jet test pattern.

Since the recorded signal is proportional to the reflectance, the reflectance modulation M_R is given by

$$M_R(\nu) = \frac{\bar{U}_2(\nu) - \bar{U}_1(\nu)}{\bar{U}_2(\nu) + \bar{U}_1(\nu)}$$

where $\bar{U}_1(\nu)$ is the graphically estimated average value of the voltage recorded for the lines of the test pattern and $\bar{U}_2(\nu)$ the same value for the adjacent spaces.

The average signal value $\frac{\bar{U}_2(\nu) + \bar{U}_1(\nu)}{2}$ is approximately constant for all spatial frequencies. Then we can write

$$M_R(\nu) = k_5 \cdot 2A(\nu)$$

where

$$k_5 = \frac{1}{\bar{U}_2(\nu) + \bar{U}_1(\nu)}$$

can be treated as a constant and

$$2A(\nu) = \bar{U}_2(\nu) - \bar{U}_1(\nu)$$

the peak to peak value of the signal for a particular spatial frequency ν .

Since this is true for all frequencies ν , the modulation transfer function $m_r(\nu)$ is obtained by

$$m_r(\nu) = \frac{M_R(\nu)}{M_R(0)} = \frac{k_5 \cdot 2A(\nu)}{k_5 \cdot 2A(0)} = \frac{A(\nu)}{A(0)}$$

After compensation for the influence of the microdensitometer as described in section 6.9, $m(\nu)$ is obtained and plotted versus the spatial frequency ν .

Plots of the MTF obtained in this way are presented in Fig. 6:13 for a 7 μm jet and in Fig. 6:14 for a 10 μm jet. Here the solid curves refer to the density range which was produced by the PDM mode method only, while the dashed MTF was created by the density range which required switching between the PDM and voltage mode. In both cases the drop formation of the jet was controlled by mechanical vibrations. All other parameters used for the production of the test patterns are shown in Table 6.2 including the density range employed, thus showing the highest and lowest density of the lines of the test pattern. In the PDM mode, the pulse repetition period has been 55 μs corresponding to 6 matrix points per millimeter. Since the triggering uncertainty mentioned earlier introduced an error of only 0.006 mm this was assumed to be negligible in the present investigation. The same is true for the time required for the switching between the PDM mode and the

Nozzle diameter (μm)	7		10	
Control electrode length (mm)	8		10	
Max. control voltage (V)	800		1200	
"Off"-state voltage for PDM (V)	500		700	
Mechanical vibration frequency (MHz)	1.25		1.03	
Drum surface speed (m/s)	3.0		3.0	
Recording line density (lines/mm)	10		10	
Modulation mode	Combi- nation	Only PDM	Combi- nation	Only PDM
Maximum density S_{max}	0.98	0.98	1.36	1.36
Input signal voltage U_{in} producing S_{max} (V)	1.4	1.4	1.4	1.4
Minimum density S_{min}	0.18	0.43	0.32	0.68
Input signal voltage U_{in} producing S_{min} (V)	4.5	3.0	4.0	5.0
v_{50} (lines/mm)	4.3	5.3	5.1	4.2

Table 6.2.

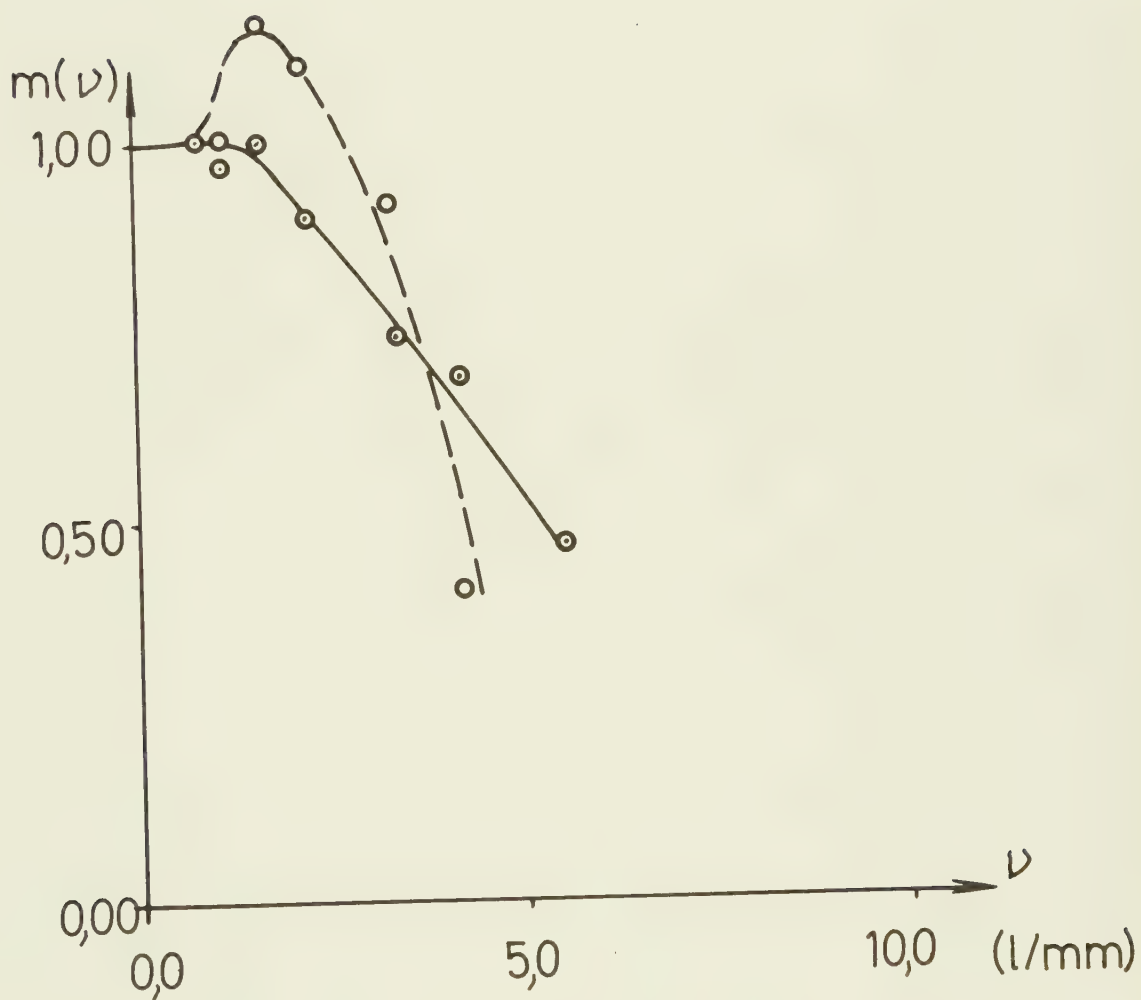


Fig. 6:13. Modulation transfer function for a 7 μm jet.
Solid curve: PDM mode only. Dashed curve:
PDM and voltage mode together.

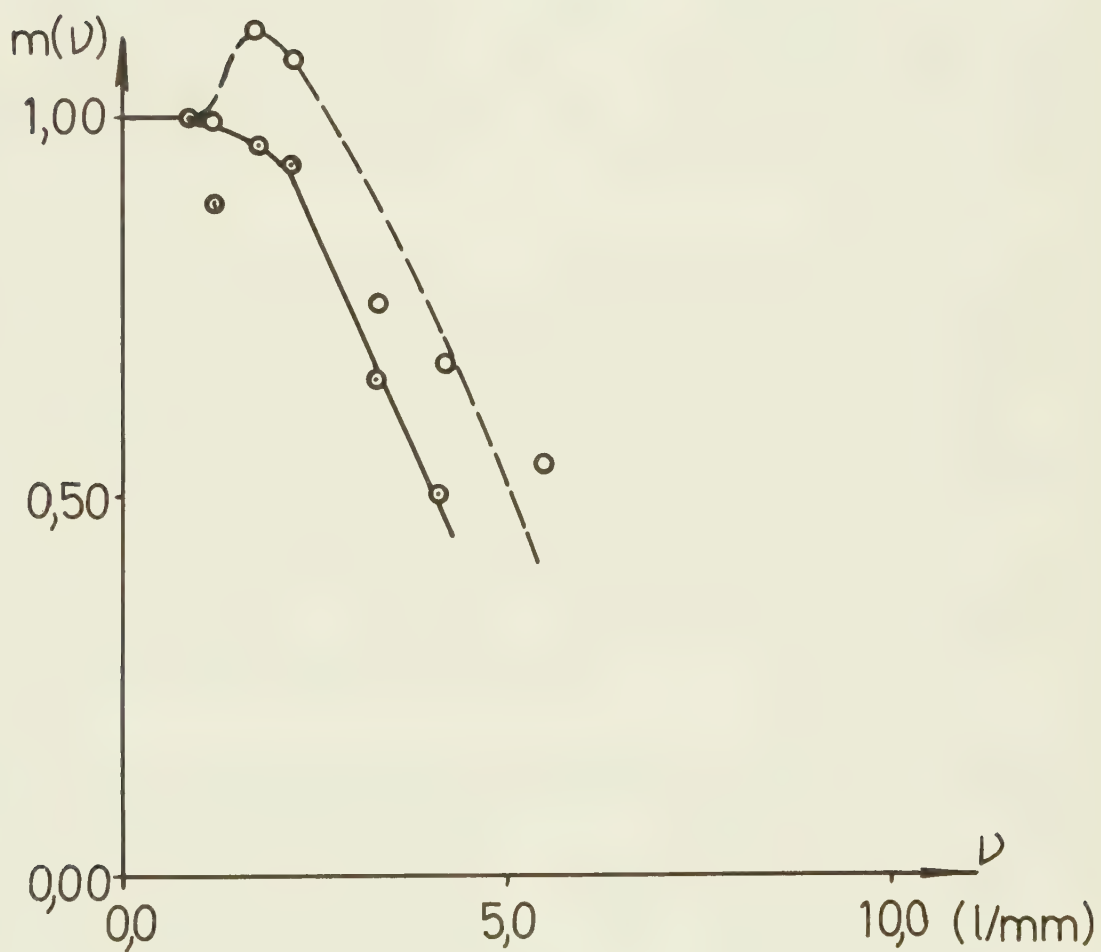


Fig. 6:14. Modulation transfer function for a 10 μm jet.
Solid curve: PDM mode only. Dashed curve:
PDM and voltage mode together.

voltage mode which was found to be approximately 15 μ s and thus corresponds to a recording trace length of only 0.05 mm.

In both figures the solid curves were obtained from patterns of such density levels that the PDM mode method alone could create the lowest and highest density of the pattern lines. Because of this these curves are very similar to Fig. 6:3 and Fig. 6:4 obtained with a pure on-off modulation method for the determination of the resolving power. Comparing the Figures 6:3 and 6:13 as well as 6:4 and 6:14 we find that the unsynchronized PDM pulses do not impair the sharpness of the image very much which is somewhat unexpected because of the relatively large duration between the PDM pulses. Since there are only six PDM pulses per millimeter, patterns with a spatial frequency of more than 3 lines/mm should not be reproduced any more by the ink jet device. However, from Figures 6:13 and 6:14 it is found that the spatial frequency, at which the MTF has fallen 50 % lies above 4 lines per millimeter.

This apparent contradiction can be explained by the fact that the rise time of the square wave signal voltage producing the line pattern is considerably less than the duration of the non-linear ramp used to create the PDM pulses. Because of this the switching between different density levels of the test pattern can take place during one period of the ramp voltage. This may change the instant when the PDM mode circuit switches the jet from the "on" to the "off" state, thereby producing a better definition of the image than one would obtain if the PDM circuit function would not be influenced by the input signal during a pulse period.

If we study the dashed curves in the Figures 6:13 and 6:14 we observe that the MTF in these cases becomes larger than 1 for certain spatial frequencies. From the definition of the MTF this is not expected because of which this phenomenon requires an explanation. By comparison with Table 6.2 it can be seen that the dashed curves were obtained from test patterns of a density range where the low reflectance parts of the pattern were created by the PDM mode method while the voltage mode method was used to print the pattern elements having a high reflectance. Thus the true combination mode method was used to produce these patterns.

In section 6.7 it was discussed, that the MTF measured with a square wave pattern will give somewhat larger values in a certain frequency range than would be obtained using a pattern with a sine wave reflectance distri-

bution. We find from Figures 6:13 and 6:14 that the MTF of the ink jet method declines sharply at spatial frequencies higher than 3 lines/mm and thus we can conclude that the square wave patterns around this spatial frequency are not truly square wave but rather sine wave patterns. Thus, MTF measurements from these patterns should give a value about 20 % higher than at lower spatial frequencies which is in good agreement with the results shown in Figures 6:13 and 6:14.

However, a closer study of the test patterns indicates that the excessive values found for the MTF are at least partly explained by the existence of the large merged edge drops at both ends of a train of uncharged ink drops which were discussed extensively in chapter 2. As mentioned in chapter 2, the existence of these large drops is due to the axial repulsion between charged drops of the jet. In the vicinity of both ends of a train of uncharged drops, this repulsion causes some of these drops to coalesce with the uncharged edge drops of the drop train, thus increasing their size and charge.

Since the test patterns used in this study of the MTF are produced by square wave pulses resulting in drop trains of uncharged drops the presence of these large edge drops becomes of importance at higher pulse frequencies. To see this we have to reconsider the definition of the MTF which is given by

$$m(\nu) = \frac{M_R(\nu)}{M_R(0)}$$

To determine $M_R(0)$ in this equation, a test pattern with a very low spatial frequency is used. In this case the large edge drops only show up as a slight increase of the density at the edges of the wide lines of the test pattern and do therefore not influence the measurement of the reflectance by the microdensitometer. On the other hand, at higher spatial frequencies the width of the lines of the test patterns is much smaller because of which the large edge drops do influence the measurement, thus decreasing the reflectance of the lines. At the same time the light areas between the lines of the test pattern become somewhat lighter since some of the charged drops used to create the lighter grey shades in the voltage mode have disappeared by the merger with the large edge drops. Thus, while the measurement of $M_R(0)$ is unaffected by the edge drop phenomenon, the value of $M_R(\nu)$ is actually increased for certain spatial frequencies. This explains the finding that the MTF for the combined mode method is larger than one for spatial frequencies of about 2 lines/mm.

For higher spatial frequencies we have found that the determination of the MTF is not quite reproducible for the dashed curves and depends on the test pattern used. The reason for this is not quite understood yet. However this observation may be explained by the fact, that the position of the matrix points generated by the PDM mode is more or less stochastic since the pulse repetition frequency of the PDM circuit is not synchronized to the drum rotation. Further, the switching between the PDM and voltage mode method requires 15 μ s in both directions. Because of both of these facts it seems reasonable that a relatively large statistical error is introduced in the reproduction process when switching from a light grey shade (voltage mode) to a darker shade, which is produced by the PDM mode. However, since this statistical error can be reduced by a synchronization of the PDM matrix and is not a fundamental defect introduced by the properties of the ink jet device this question will not be discussed further here.

The investigation of the MTF of the ink jet device described above obviously does not represent more than a rough estimation of this property. However, since the present report is aimed at a general study of all the aspects influencing the capability of this new device, no additional efforts were made to find the MTF also for other jet diameters or to increase the precision of the measuring method used here.

7. DETERMINATION OF THE GRANULARITY OF GREY SCALE PATTERNS

7.1. Introduction

The quality and definition of images produced by any kind of reproduction process are not determined by its resolving power or MTF alone. Another factor decreasing image quality is due to stochastic variations of the density in half tone areas, the average density of which is constant. This phenomenon is commonly called graininess. As an example the photographic film can be mentioned. Its graininess is caused by the stochastic distribution of the silver grains in the emulsion. In photography the subjective impression of this irregularity is called graininess while the objective measurement of this quality yields the granularity.

Besides decreasing the quality of the grey shades the graininess also decreases the sharpness of the boundaries between different shades of grey. Because of the procedure used for the determination of the MTF the graininess does not necessarily enter into these measurements as long as it is approximately equal to or smaller than the v_{50} -value.

Images produced by the ink jet device also show graininess which can be detected already with the naked eye at close inspection. The fundamental cause of this graininess is the fact that an ink jet consists of separate drops of ink, the diameter of which is about 1.5 - 2 times the ink jet diameter (cf. chapter 2). When a grey shade is to be printed by the voltage mode method these drops are dispersed into a spray by charging the drops electrically. Only the central part of this spray is then allowed to reach the recording paper through the small aperture at the farther end of the control electrode. Obviously, the drops will settle on the paper in a stochastic manner thereby creating graininess of the trace. Further, if the PDM mode is used to create the grey shade, an unsynchronized PDM matrix is generated on the paper by the present apparatus which may also show up as a graininess of the image. This is especially true if the PDM mode is used to create light shades of grey which require "on" pulses of less than 10 μ s duration. For reasons already explained in chapter 5 not every PDM pulse is deposited on the paper which also gives rise to a pronounced graininess.

The modulation transfer function and the granularity in conjunction chiefly determine the image forming capability of the ink jet process and hence its ability to reproduce the information contained in the original image. As the size of the details in the images grows smaller, the limited spatial frequency range of the MTF deteriorates their reproduction and makes the recognition of such details increasingly difficult. Likewise, the smaller the size of the details the more difficult it is to distinguish them due to the deteriorating effect of the graininess. Thus, both these factors impose a limit on the ability to detect or recognize details in the images. Because of this, the graininess of grey shades generated by the ink jet device will be investigated in this chapter. Further, to judge the capacity of the ink jet device correctly its granularity should be compared with, e.g., the spatial irregularity in density observed in highly magnified photographic film which is due to the inhomogeneous arrangements of silver grains. However, before reporting this investigation, different approaches to the measurement of the granularity will be discussed.

Different objective methods to measure granularity of photographic material have been investigated by several authors. Thus Threadgold (1932) found that the ratio of specular to diffuse density, which was easily measured, showed a certain degree of correlation with subjective estimates of the graininess of the material. Another method was proposed by Romer and Selwyn (1943) in which the granularity value was defined as the smallest test pattern that could be distinguished from the granularity. However, both methods were sometimes in disagreement with the subjective impression of graininess.

A more theoretical approach was made by Selwyn (1935) who studied the density variations in microdensitometer traces. Selwyn showed that the deviations from the mean value of the density followed a Gaussian distribution under certain conditions. As a result of his investigation he defined the so called Selwyn granularity G :

$$G = (2a)^{1/2} \cdot \sigma_a$$

where a is the circular area of the scanning aperture of the microdensitometer and σ_a the standard deviation of the density values.

This definition of granularity has been carefully examined by several authors and it has been shown that G is independent of the area of the scanning aperture for a certain film material provided the density variations are

small and the density values uncorrelated to each other. This was proved by Higgins and Stultz (1959) by measurements on samples which did not contain any correlated density variations in the form of scratches, dust, fingerprints and the like.

Since Selwyn's definition of the granularity is widely in use, this method was also accepted for the present determination of granularity of ink jet images. To this end the output voltage of the microdensitometer was measured, when a sample of a constant grey shade fastened to the drum shown in Fig. 6:2 was moved under the microscope objective. Further details of this procedure will be discussed in the following. However, before describing the actual measurements in section 7.4, a short introduction to the theory will be given in section 7.2. whereafter the production of the test patterns is described in 7.3.

7.2. Theory for the measurement of granularity

Let us consider a test pattern with an average density of $\bar{S}$, the density of which is measured in n sample points with indices i by a microdensitometer with a circular aperture of area α . Further, suppose that this area α is large compared with the size of the grains causing the granularity, and that the density values for the sample points are independent of each other. Then the variations of the density values obtained by the separate measurements from the average value $\bar{S}$ approximately follow a Gaussian distribution. This distribution implies that the probability that a certain value lies in the interval (S, dS) is given by:

$$P(S, dS) = f(S) \cdot dS = (2\pi\sigma_\alpha^2)^{-1/2} \cdot \exp -\frac{(S-\bar{S})^2}{2\sigma_\alpha^2} dS$$

where
$$\bar{S} = \frac{\sum_{i=1}^n S_i}{n}$$

is the average value of the density

and
$$\sigma_\alpha = \left(\frac{1}{n-1} \sum_{i=1}^n (S_i - \bar{S})^2 \right)^{1/2}$$

is the standard deviation of the density values obtained from the n measurements made with the aperture area α .

Provided that the assumptions made above are valid, then (Selwyn 1935):

$$\sigma_a \cdot a^{1/2} = \text{constant}$$

i.e. the standard deviation for the density values obtained with the aperture area a , multiplied by the square root of that area is constant. According to Perrin (1966), the definition of the Selwyn granularity is approximately equal to this constant, i.e.

$$G = \sigma_a \cdot (2a)^{1/2}$$

7.3. Production of the test patterns

The test patterns required for the measurements of the granularity should consist of areas having constant average density. Such test patterns were already made for the investigation of the grey scale capabilities of the ink jet device, and the technique used for the generation of the patterns is described in section 5.5. In a preliminary investigation these test patterns were used to find the density levels at which the granularity was most annoying to the human eye. Thereafter new test patterns for these density levels were produced by the combination mode method according to the technique described above. This was done to avoid measurement errors due to the bleaching of the test patterns, which can be observed after several days if blue ink supplied by the Elema Schönander Company is used on baryte paper. In this way it was ensured that really the worst case of granularity produced by the ink jet device was determined.

7.4. The measurement of granularity in ink jet images

The granularity of a photographic film is measured by scanning a uniformly exposed and processed film sample having constant average density with a microdensitometer using a small circular aperture. This aperture defines the area of the film a , the density of which is measured. Using this arrangement the local density of a large number of sample points on the film is recorded. When the average density of the film sample has been determined, the difference between the local density of each sample point and the average density can be calculated from which the standard deviation σ_a of the density variations of the sample can be determined. From the σ_a and the aperture area a the granularity can then be calculated as shown above.

For the measurement of the density variations of the samples produced by the ink jet device, the microdensitometer shown in Fig. 6:2 was used. However, the long and narrow slit was replaced by a circular aperture plate for these measurements. The choice of an appropriate diameter for this aperture will be discussed below.

The light intensity reflected from a small element of the sample under investigation was detected by the photomultiplier through the circular aperture. Thus the output current of the photomultiplier is proportional to the reflectance of this sample element. After amplification, the signal was recorded on a strip chart recorder in the same way as described earlier in section 6.4. describing the measurement of the resolving power. A typical record is shown in Fig. 7:1.

According to the definition of the Selwyn granularity, the density of the n elements measured in the test pattern is required for the determination of the granularity. Therefore, the voltage signal values obtained with the microdensitometer have to be converted into density values. To achieve this, calibration levels of known average density generated separately on the test pattern were recorded on the strip chart together with the recording of the granularity measurements as shown in Fig. 7:1. The average density S_{kv} of each of these calibration levels was then measured with the reflection densitometer described in section 5.5. and used to calibrate the strip chart record of the reflectance variations measured by the microdensitometer. In this way the voltage signal recorded on the strip chart could be directly translated into density by graphic interpolation.

It has been pointed out earlier, that the area of the scanning aperture should be chosen in such a way that the differences between the density of each sample point and the average density show a Gaussian distribution. If this is the case

$$\sigma_a \cdot a^{1/2} = \text{constant}$$

which is therefore a criterion for the condition stated above. Hence this criterion was used to find a suitable scanning aperture for the measurements.

To this end a preliminary investigation was made in which microdensitometer records were obtained from a suitable test pattern using four different aperture sizes. With each aperture the reflectance at 25 sample points on the test pattern was measured and recorded by the strip chart recorder.

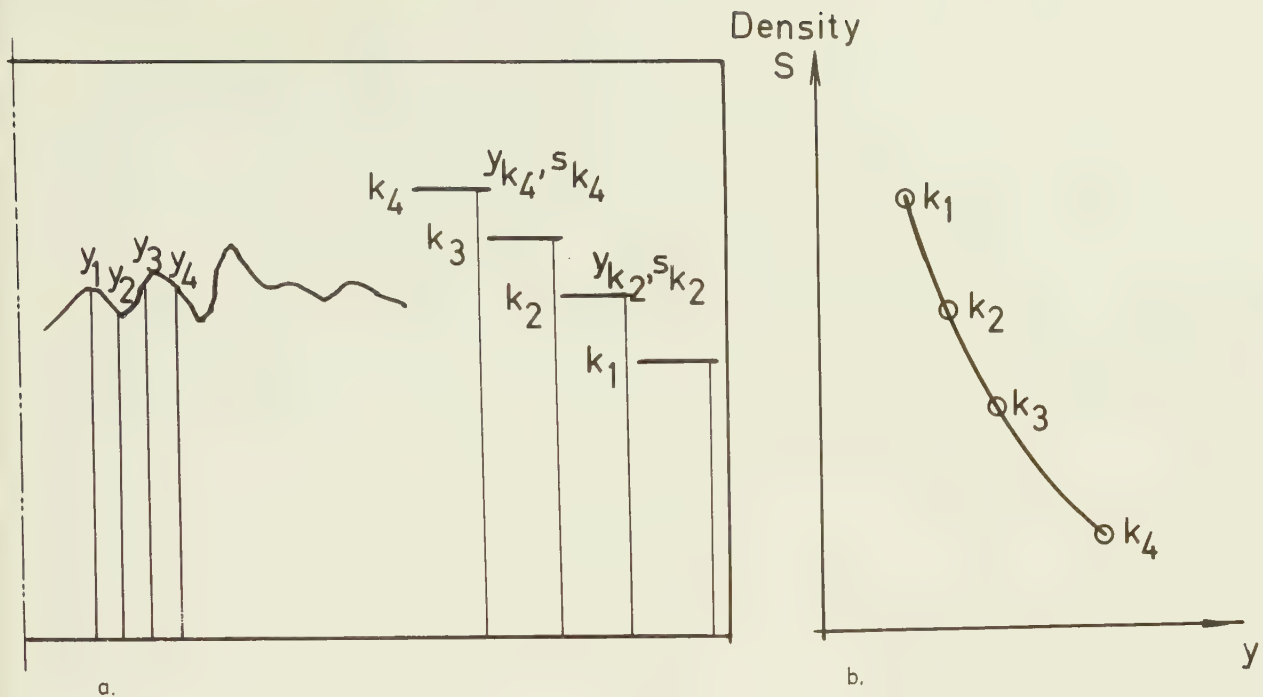


Fig. 7:1a. Strip chart recording obtained from granularity measurements.

b. Curve obtained by means of the calibration levels k_y in a., used for the translation of the recorded voltage signal into density.

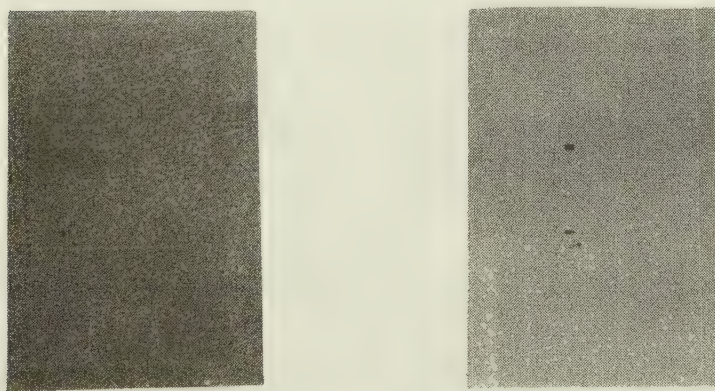


Fig. 7:2. Photographic test samples for granularity measurements.

The distance between successive sample points was chosen equal to one aperture diameter in order to avoid any correlation between the measurements. These reflectance measurements were then translated into density, whereafter σ_a was calculated from these 25 density values. Multiplying σ_a with the square root of the area of the aperture used in the four different experiments, the following results were obtained (table 7.1). The diameters given in this table and the following refer to the size of the image of the actual aperture on the drum surface and thus define the measuring area.

Aperture image diameter $d(\mu\text{m})$	$\sigma_a \cdot a^{1/2}$ (μm)
65	9.9
160	19.4
300	18.5
800	--

Table 7.1.

For the smallest diameter of $65 \mu\text{m}$ the requirement that the diameter should be considerably larger than the grains in the sample is obviously not fulfilled. On the other hand, when a diameter of $800 \mu\text{m}$ was used the density variations were too small to be recorded by our microdensitometer with sufficient accuracy. However, the apertures with a diameter of $160 \mu\text{m}$ and $300 \mu\text{m}$ seem to fulfil the relation $\sigma_a \cdot a^{1/2} = \text{constant}$ and are therefore suitable for the present measurements. For the measurements reported in the next section, an aperture diameter of $300 \mu\text{m}$ was used.

7.5. Results of the granularity measurements

In order to correlate the granularity determinations made with our microdensitometer reported below with a known object a photographic film of relatively high graininess (Kodak Tri-X) was exposed and processed uniformly in such a way that a transmission density of approximately 1.0 was obtained. This film was then printed 5 times enlarged on a medium glossy light sensitive paper (Agfa Brovira Normal) resulting in an average reflection density of 0.81 and on a soft printing paper (Agfa Brovira Weich) resulting in an average density of 0.51. These samples are presented in Fig. 7:2. The local density of 25 sample points was then measured as described above, the distance between the sample points being $300 \mu\text{m}$. All the

samples were lying on the straight line between the two marks in Fig. 7:2. This was achieved by mounting the sample on the drum of the microdensitometer and turning this drum slowly while recording the local **reflectance** on the strip chart recorder. From this record, the local density at the sample points could then be determined as described above. Using these values and the average density of the sample the value of σ_a and the granularity were calculated. The results are given in Table 7:2.

Usually the granularity values for photographic film material are given for an average density of 0.8 since the graininess is considered most annoying at this density level. A subjective estimation of ink jet images indicated instead that the graininess for such images was highest for the density levels around 0.5. A preliminary test measurement verified this. The reason for this is that the switching between the pulse duration modulation and the voltage mode modulation takes place at a density level slightly lower than 0.5. Thus the grey shades are generated by the PDM modulation by pulses creating very short drop trains. This gives rise to a high graininess according to the discussion in section 5.7.

For the test patterns made with density levels of about 0.5 the granularity was evaluated in the way described above. The results of this evaluation are presented in Table 7.2.

It was observed earlier that the difference in resolving power was small between images produced with and without controlled drop formation if a 7 μm nozzle was used. In spite of this a considerable deterioration of the quality of grey scale reproductions could be observed with the naked eye if no drop formation control was used. The large difference found in Table 7:2 for the granularity of the two types of test patterns explains this finding readily. This is due to the fact that drops formed by a spontaneous drop formation process are irregular in size because of which they merge much more easily than the equal sized drops generated by vibration control of drop formation. Further, the number of drops created per second is appreciably lower in the case of spontaneous drop formation than if this process is controlled by mechanical vibrations of suitable frequency as was shown in chapter 2.

The measurements reported in Table 7:2 cover only a very limited range of ink jet parameters applicable to image reproduction and were made only to investigate general tendencies of the influence of these parameters

on ink jet image graininess. Therefore, only such parameters were chosen which gave the best image quality in the experiments described in chapter 8. However, from Table 7:2 it can be deduced that the graininess increases with jet diameter. Further, from the experiments with a 7 μm nozzle we can conclude that the graininess is strongly dependent on the control of the drop formation process by mechanical vibrations. This dependence was not measured for a 10 μm nozzle, but visual inspection of the granularity obtained with and without control using a 10 μm nozzle showed clearly the same tendency.

Ink jet test patterns					
Drum surface velocity	Scanning line density	Nozzle diameter	Drop formation control frequency	Average density	G
m/s	lines/mm	μm	MHz	$\bar{S}$	μm
3	10	7	--	0.53	27.3
3	10	7	1.25	0.44	13.8
3	10	10	1.03	0.50	17.1
Reference patterns					
Tri-X on Brovira Normal				0.81	22.4
Tri-X on Brovira Weich				0.51	13.9

Table 7.2.

8. REPRODUCTION OF IMAGES

8.1. Introduction

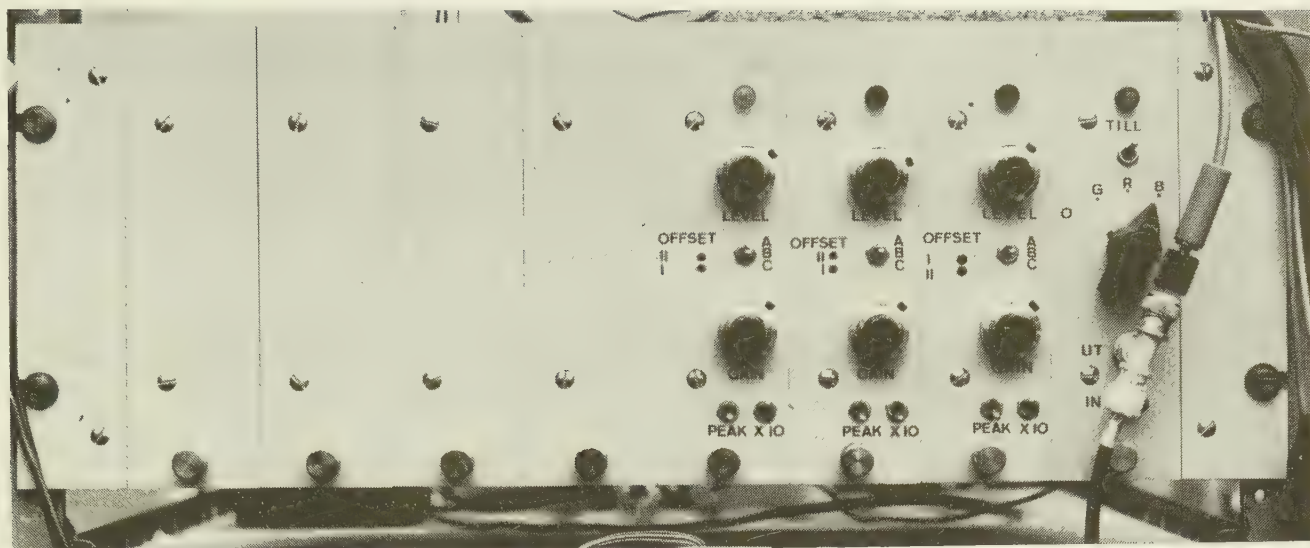
In the earlier chapters of this report different aspects of the properties of a new recording device using an ink jet were studied especially with its possible application to the reproduction of images in mind. In this chapter actual reproductions of different kinds of images will be demonstrated and their quality compared with the fundamental properties of the ink jet device determined in the investigations described earlier.

First of all the capability of the ink jet device for the reproduction of images consisting of black and white details only is demonstrated in section 8.2. using suitable test patterns. In section 8.3. images containing even grey shades are studied. Only the combined mode method for the modulation of the ink jet was used in this case. A special method for the generation of grey shades using the PDM mode method only was developed for recording images transmitted from weather satellites which will be described in section 8.4.

Since inks are obtainable in different colours, even colour reproductions have been made with the ink jet device studied here. In section 8.5. the procedure used in these experiments is described and the results obtained in this way are discussed.

The ink jet device represents a typical non contact printing method since no mechanical devices touch the record receiving surface during the printing cycle. Because of this very small demands are made upon the surface qualities of the record receiving surface. This is demonstrated in section 8.6. which shows the capabilities of the method to print even on surfaces with a rough texture with good definition.

Excepting the satellite recordings, all the reproductions described in this chapter were produced on the apparatus shown in Fig. 8:1, in which two rotating drums were used to carry the original and the recording paper. The speed of rotation was 900 rpm, the drum diameter 62 mm and the drum surface speed 3 m/s. Even here, a scanning line density of 10 lines/mm was used throughout. Using these parameters, a 13 x 18 cm image could be



a.

b.

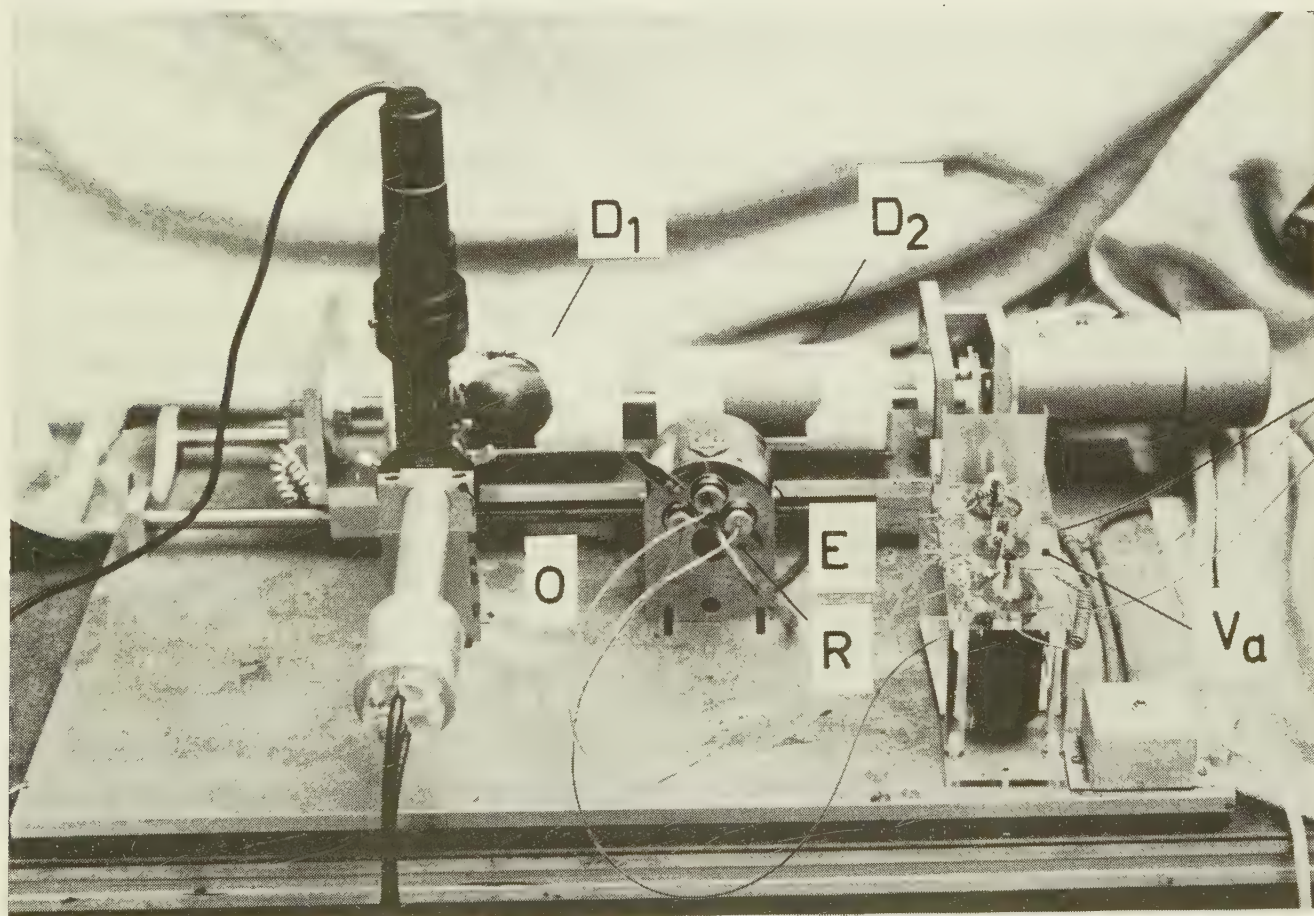


Fig. 8:1. Experimental apparatus for the generation of ink jet reproductions.

a. Preamplifiers used for colour reproductions.

b. Rotating drum equipment used for one- as well as three-colour reproductions.

printed by the ink jet device in 85 seconds. Since the drums of the apparatus were of equal size, the reproduction scale was 1:1.

8.2. Black and white image reproduction

For the reproduction of pure black and white images, the ink jet device was operated only in an on-off-mode to obtain the maximum resolution possible. For the same reason baryte paper was used as the recording surface and a nozzle diameter of only 7 μm with controlled drop formation was employed. In most of the experiments, blue ink supplied by the Elema-Schönder Company was used, the dye concentration of which was about three times as high as that used in their ink jet oscillographs. No difficulties were experienced with this ink. However, some recordings were made also with other inks including black ink, which gave the same quality according to a subjective estimation. Thus, within limits, the properties of the ink do not seem to influence the image quality appreciably.

The image quality which is obtained in this way is demonstrated by Fig. 8:2 which shows the reproduction of a black and white test pattern in natural size. The apparent grey scale contained in the reproduced test pattern is generated by point to point reproduction of matrix points in the original which can be seen in Fig. 8:2b showing an enlargement of a certain part of the original test pattern. Fig. 8:2c shows a magnified print of the same area in the reproduction. The magnification of the latter two figures is about three times and the actual dimensions can be judged by comparison with the millimeter scale on top of the figures, which was copied together with the test patterns.

In the ink jet reproductions the quality of the ink jet images was quite satisfactory to the naked eye, which can also be seen in the print in Fig. 8:2a. The relatively unsatisfactory appearance of the reproduced grey scale matrix points is caused partly by the linear scanning of the original producing a kind of Moiré effect and partly by the subsequent photographic reproduction for this publication. The scanning of this area causes a typically oblique line pattern which can be seen clearly in Fig. 8:2 and which is due to an interference between the arrangement of the matrix points of the original and the scanning lines. In spite of this, the nine different grey shades could be easily discerned in the original ink jet reproduction.

Testvorlage 9300 v.8.5.67

nach Cordonnier

für Gefafax – System




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8

9

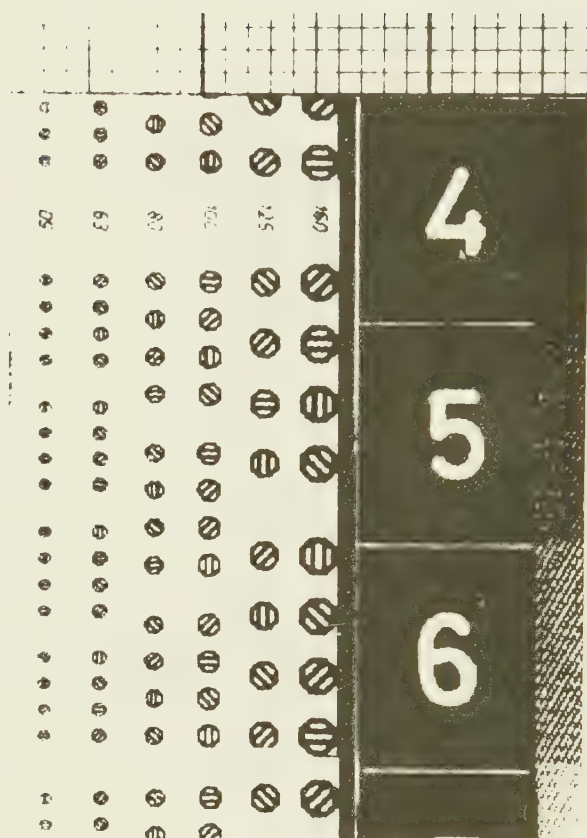
Meßwerte und Einstellungen

Typ	
Gerät	F.Nr.
Papier	Nr.
Toner	Nr.

Fig. 8:2a. Reproduction of black and white test pattern in natural size.



a.



c.

Fig. 8:2b. Magnification of the original test pattern for the reproduction in a.

Fig. 8:2c. Magnification of the reproduction in a.

From a comparison of the magnified prints shown in Fig. 8:2b and 8:2c we find that the lines in the hexagonal small test figures can be discerned as far as the vertical column denoted 63. With the help of the millimeter scale at the top of the figures we find that the equivalent line density is about 7 lines/mm which agrees well with the resolving power determined in section 6.5. for the on-off modulation of a 7 μ m jet using controlled drop formation.

However, a certain loss of quality due to the reproduction method used here can be observed by inspection of the large white figures 4, 5 and 6 in the magnified print of the original and the reproduction. By measurements we can find that the size of these figures is diminished with approximately 0.05 mm along the boundaries in the reproduction as compared with the original. This phenomenon can also be observed in the white lines between the figures, the width of which is decreased in the reproduction. This is probably caused by stray light in the optical scanning device influencing the setting of the switching point of the on-off electronic circuitry. In this case the switching was adjusted in such a way that the hexagonal figures in the test pattern were reproduced as well as possible. Since these figures are mostly surrounded by large white areas, the influence of the stray light from these areas generated in the lens system etc. was taken into consideration when determining the video signal voltage at which the electronics switch the ink jet from the "on" into the "off" state. Now, the figures 4, 5 and 6 as well as the fine white lines surrounding these figures are situated on a black area. Thus no stray light is generated in this case, because of which the setting of the electronic circuit should here be changed to obtain the correct reproduction. Since this cannot be done in practice, more attention should be given to the construction of the optical system to diminish the stray light generated there.

8.3. Half-tone image reproduction

For the half tone images discussed here, the combination mode method was used as described in sections 5.8. and 5.10. To obtain maximum image quality, even here a 7 μ m nozzle with controlled drop formation as well as baryte paper and blue ink was used as described in the previous section. The use of baryte paper was especially advantageous in this case since it shows better contrast than e.g. ordinary typewriter paper, thereby increasing the density range obtainable.

A typical result obtained in this way is shown in Fig. 8:3. Here, Fig. 8:3a again shows the reproduction in its natural size while the figures 8:3b and 8:3c are magnified prints of a certain part of the original and the reproduction respectively. The millimeter scale at the bottom allows even here the estimate of the degree of magnification. In this case, the original was a magnified print made on ordinary photographic paper from a 24 x 36 mm Tri-X photographic film.

Again, the subjective quality of the ink jet reproduction appears to be almost satisfactory to the naked eye. However, in certain parts of the image the scanning lines can be seen faintly. This is due to the relatively low line density which makes very high demands on the precision of the spindle drive causing the relative movement between the ink jet and the drum. Further, small details do not show up as well as in the original which is especially true for certain density ranges. This is probably partly due to the error in the characteristic curve of the combined mode electronics and partly to the decrease in maximum density range from about 2 for the original photographic print to about 1 in the ink jet reproduction. It should be observed, that the photographic reproduction of the ink jet image in Fig. 8:3 does not faithfully show this decrease in density range. Of course also the graininess generated by the ink jet device as well as the limited bandwidth of its modulation transfer function decrease the resolution of the method for small details.

The magnified print of the ink jet image (Fig. 8:3c) discloses the transition between the voltage mode and the PDM mode method for example in the folds of the girl's hood. The relatively high granularity created by the PDM mode makes it easy to distinguish between elements in the picture created by the two different modes.

Generally, apart from the difference in density range, the main difference between the original photographic print and the ink jet reproduction seems to be the larger granularity of the reproduction. While it should be possible to increase the density range by the development of a more suitable ink and a higher scanning line density, the granularity can only be decreased by the use of smaller nozzle diameters. A nozzle diameter of 4 to 5 μm would probably still present a feasible improvement, but nozzle diameters around 1 μm are not a realistic approach to the graininess problem. The reason for this is that it will probably not be possible to build an ink jet system working reliably with a 1 μm nozzle since such small nozzles are easily clogged by small particles in the ink and require very high pressures to create jets with acceptable



Fig. 8:3a. Reproduction of half tone image in natural size.



Fig. 8:3b. Magnified print of the original photographic image used to generate the reproduction shown in Fig. 8:3a.



Fig. 8:3c. Magnification of the reproduction shown in Fig. 8:3a.

volume flow rates.

It has been reported earlier, that the 13 x 18 cm size reproduction shown in Fig. 8:3 is printed in 85 seconds by the present apparatus. Obviously, this print-out time could be shortened by increasing the speed of rotation of the drum or decreasing the scanning line density. It is easily seen that this would decrease the resolution of the images, but it should also be observed that the maximum density range obtainable in the image is decreased simultaneously. This latter disadvantage can at least partly be counteracted by using higher ink pressure, larger nozzle size and an ink of higher density. However, it should be kept in mind that the parameters named above are interdependent and that a suitable compromise has to be found depending on the requirements made by the special recording problem in hand.

8.4. Recording of images from weather satellites

To study the application of the ink jet device to more practical problems pictures obtained from the earth surface by the camera of weather satellites were recorded. The video signal from the weather satellite was received and demodulated by a receiver station built by the Department of Applied Electronics at the Lund Institute of Technology (Stigmark et al. 1970). Normally, these signals were then used to modulate a light emitting diode which exposed a photographic film mounted on a rotating drum arrangement. Since the film on the drum has to be kept in absolute darkness during the recording and required development it was felt that the ink jet method might provide a convenient alternative. The necessary electronic circuitry for this study was built by Backlund and Tuveßon (1971) as part of their diploma work. Even in this case a rotating drum arrangement was used to provide the necessary relative movement between the recording paper and the ink jet device.

The video signal from the camera of the weather satellite is transmitted by amplitude modulation of a subcarrier frequency of 2400 Hz. This video signal which transferred the original image line by line was recorded together with a stable reference frequency of 2400 Hz on a double track tape recorder. The reference frequency was electronically divided in a suitable manner and used to control an electronic 220 Volts AC generator which delivered its power to a synchronous motor rotating the drum onto which the recording paper was fastened. In this way exact synchronization between the drum rotation and the video signal was ensured.

Since the speed of rotation of the drum was governed by the line frequency of the video signal, the parameters of the drum recorder used here had to differ very much from those described earlier in this paper. Therefore, the drum, the diameter of which was 57 mm, rotated at a speed of 240 rpm. This resulted in a surface velocity as low as 0.72 m/s. Every image consisted of 600 lines recorded with a line density of 5 lines/mm. The effective size of the image obtained in this way was 12 x 16 cm, which is somewhat smaller than expected from the circumference of the drum (18 cm). This is due to the fact that a certain time is required at the end of each line to transmit a signal for synchronization purposes. The recording time for one picture was 2.5 minutes.

Since the surface speed was relatively low the demands made on the upper frequency limit of the intensity modulation process was not too high. Therefore, a 15 μ m nozzle was chosen for the ink jet device because of the larger density range generated by this jet compared to a 10 μ m nozzle. This was especially desirable because of the relatively low line density which otherwise would have decreased the image contrast appreciably.

For the generation of the grey scale in the picture a pure PDM modulation mode was chosen. This was partly due to the fact that the peculiar form of the subcarrier wave from the satellite was especially suited for this type of grey scale mode and partly since the low surface speed of the drum seemed to allow a simplified grey scale electronics without losing too much information. In this case the duration of the PDM mode pulses was approximately 200 μ s.

Fig. 8:4 shows a result obtained with this apparatus. Here four pictures transmitted separately after each other by the weather satellite were joined together thereby producing a survey map of Europe in the north-south direction. The boundaries between the separate recordings show up as horizontal lines in the figure. For the orientation of the reader it can be mentioned that the picture covers most part of Europe and Northern Africa. The island of Gotland (upper arrow) and the Sinai peninsula (lower arrow) can be clearly distinguished in the picture.

A relatively good half tone reproduction is obtained in these images due to the low surface speed of the drum in spite of the fact that only the PDM mode was used to generate the grey shades. However, even here problems arise in the low density range where the grey shades show high graininess. Further,

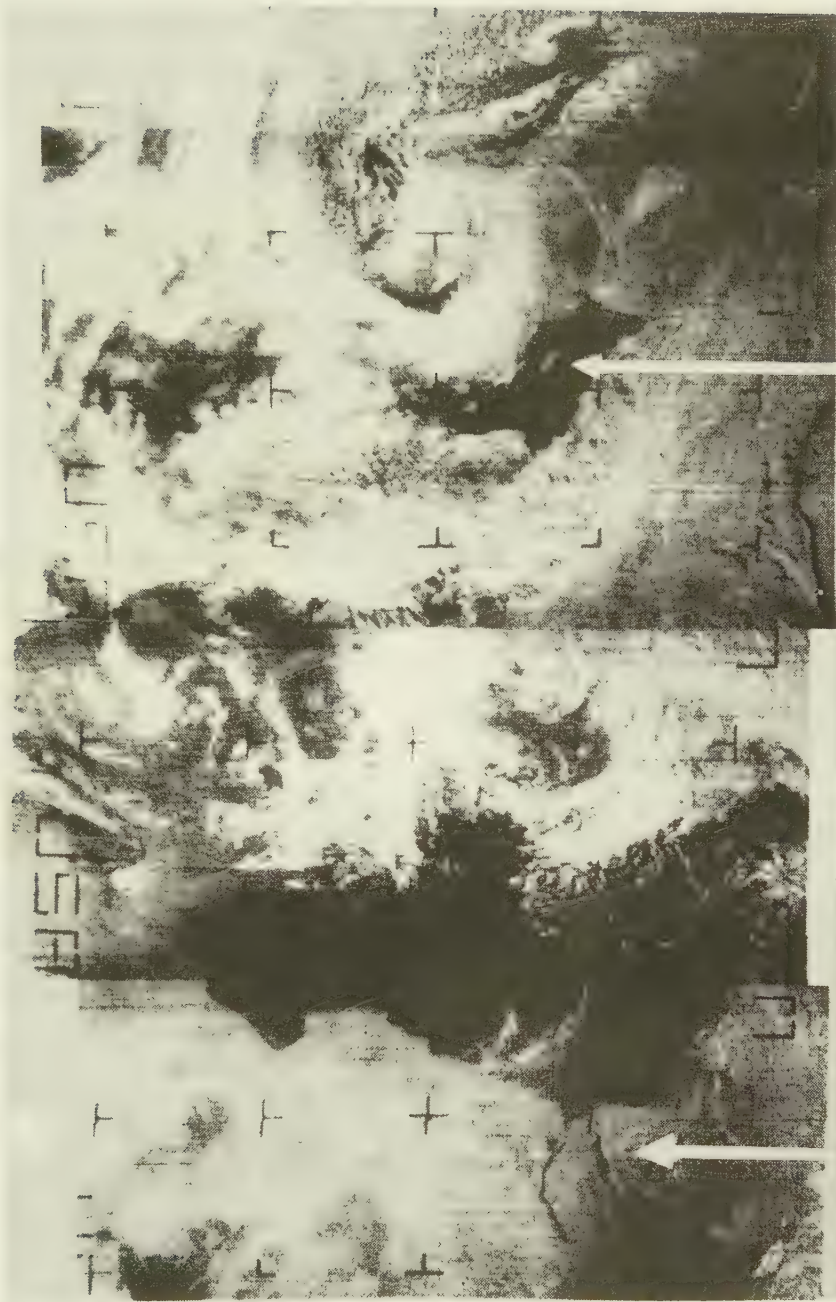


Fig. 8:4. Ink jet recording of weather satellite picture. Upper arrow: Gotland, lower arrow: Sinai peninsula.

when the density is decreased even further, the reproduced grey scale drops abruptly to white as observed earlier in section 5.7. Even here this phenomenon is due to the behaviour of the large edge drops in front of and at the end of each train of uncharged drops. Thus even in this case the use of the combined mode electronics would have increased the image quality appreciably. However, it should be mentioned here, that some of the image quality was already lost by signal distortion introduced by the tape recorder used in these experiments.

8.5. The reproduction of colour images

8.5.1. Introduction

Since ink can be prepared in different colours, it should be possible to reproduce even images containing colour, e.g. colour photographs. It was, therefore, of interest to study the ink jet method with respect to its capability to reproduce coloured images.

To this end use is made of the fact that the human eye cannot distinguish between a colour with a complex spectrum and a corresponding three colour mixture. This fact is applied both in colour photography and the printing of most coloured pictures, where all but the most saturated colours are represented by a proper mixture of a certain set of three basic colours. Since this method gives very acceptable results it was also chosen for the reproduction of coloured images by the ink jet method. Thus, in principle, three jets of ink representing a suitable combination of colours were used together with the combined mode method already described for single colour reproductions.

If three images produced by these three jets are superimposed on each other it is obvious that ink drops from the different jets frequently reach the recording paper at the same place. Thus in many instances, the different inks will be deposited on the paper on top of each other. This phenomenon is experienced even, e.g., in colour printing and it is well known that in this case subtraction colour combinations should be used. Subtractive colours are made from dyes which in principle subtract one third of the spectrum of visible light and transmit the complementary two thirds. As an example we can consider a dye which subtracts the blue part of the spectrum and transmits the green and red parts of it. Together these two parts appear

then yellow to the eye. This method of colour mixing is called the subtractive method as opposed to the more obvious additive method, which requires a spatial distribution of the different colour elements in such a way that the elements never overlap each other. A typical example for this is the screen of a colour TV tube. In the additive method, dyes can be used which transmit only one third of the visible spectrum, preferably blue, green and red, while in the subtractive method, the paper colour triple should be yellow, magenta and cyan (cf. e.g. Weissberger 1966). Thus for the ink jet experiments the latter colours were used.

8.5.2. Experimental procedure

For the reproduction of colour images the same experimental apparatus was used as for the single colour reproductions (cf. Fig. 8:1). However, this equipment was supplemented by three preamplifiers, one for each colour as well as three 7 μ m glass capillaries producing ink jets of the three basic colours yellow, magenta and cyan. These capillaries were fitted into a revolving head R in front of the common control electrode E (Fig. 8:1). By turning the head R each of the three capillaries could be placed in such a position that the ink jet produced by that capillary traversed the control electrode and passed the aperture at its far end. For better accuracy, the capillaries could be adjusted individually and the three angular positions of the revolving head, which placed each of the three capillaries in just the right position in front of the control electrode, were well defined by a mechanical spring device. The ink was supplied to the three capillaries from three separate ink containers for each colour through the valves V_a and the necessary pressure was generated by applying 30 atmospheres of pressurized air to these containers from a common pressure source.

Except for these elements, none of the other parts of the apparatus was built in triplicate. This was avoided to minimize the constructional changes of the original apparatus necessary for the conduction of the colour experiments, thereby saving time and expenditures. Because of this not all three colours could be applied to the recording paper simultaneously when making a reproduction, instead each colour had to be recorded in a separate run as described below. However, preliminary experiments showed that it would be possible to apply the three colours simultaneously which would cut down the recording time by more than a factor of three. Even if the jets met the paper very shortly after each other, no blurring of the colours could be observed.

This is due to the fact that the jet impinges upon the paper at very high speed and is thereby propelled into the paper texture in most papers. Hence the record trace is almost instantly dry which explains the absence of blurring.

From the description given above it is clear that only one electro-optical scanning device was needed for these experiments. As before, this consisted of the microscope objective O in front of the drum D_1 , which carried the original (cf. Fig. 4:1 and 8:1). This objective O supplied also the illumination of the picture element situated exactly under the objective by a lamp, the light of which was reflected through a suitable lens system onto the drum D_1 (cf. Fig. 4:1).

When producing colour reproductions, a suitable colour filter was introduced into the path of the light from the lamp to the drum surface for each run with one of the coloured inks, thereby causing a colour separation of the light reflected from the coloured original on the drum D_1 . The choice of these filters was determined by the fact that the originals to be reproduced were photographic colour prints using the basic subtractive colour triple yellow, magenta and cyan. In accordance with the definition of subtractive colours, the coloured dye deposited on the paper of the original serves as a non-transparent filter for light from that third of the spectrum which constitutes the complementary colour to the colour of the dye. Thus, for the control of an ink jet having a certain colour, a filter producing the complementary colour to the ink colour should be used in the light path from the illuminating lamp. Further, this complementary colour should contain only about one-third of the visible spectrum.

To discuss a more specific example let us assume that we want to control the yellow ink jet. Now, if blue light is used to illuminate the original image under the scanning device, this light will be reflected from those parts of the image which are made up only of the magenta or cyan dye, while it is totally absorbed by a patch of yellow dye. Thus, when the scanning device is positioned exactly over the yellow patch, no light reaches the photomultiplier tube in the scanning device, because of which its output will be low. This gives a low input signal to the combined mode electronics which will cause the ink jet to deposit a high density of yellow ink on the corresponding point on the reproduction. By a similar reasoning we find, that no yellow ink will be allowed to reach the recording paper if a pure magenta or cyan colour is placed under the scanning device. Thus, for controlling the yellow ink jet, a blue filter should be used in the light path of the illumination device. In a

similar way it can be shown that a green filter should be used for the control of the magenta ink jet and a red filter for the cyan ink jet. Colours of the original consisting of mixtures of the basic colour triplet will then automatically be reproduced by a similar mixture of inks. However, it should be observed that the spectral properties of the dyes in the ink do not meet those required for a good basic dye triplet which makes up the original image. Further, the combination mode electronics does not have an exactly linear characteristic. Because of these facts as well as the relatively low density created by the inks available at the time of the experiments, certain errors in the colour reproduction appear.

The final choice of filters used for colour image reproduction depended of course on the exact spectral composition of the inks used. These filters belonged to a colour triplet of the Agfa Gevaert broadband colour separation series, the transmission spectra of which are given in Fig. 8:5 together with their classification numbers.

The scanning device used in these experiments was the same as that applied for the preparation of the mono-coloured reproductions described in section 8.1. with the exception of the photomultiplier tube. In order to expand the spectral sensitivity towards the red region of the spectrum, the Philips photomultiplier XP 1117 having an S-20 wave length dependence replaced the XP 1110 tube. Since the sensitivity of the photomultiplier is changing very much with wavelength, three different preamplifiers were built for the three colours, the output of which was fed into the combined mode electronic circuitry common to all colours. In this way, the amplification as well as the DC-level could be adjusted individually for each colour.

Thus, when a colour picture was reproduced with this machine, three runs were made one after another on the same recording paper, each run producing a one-colour reproduction of the original. Before each run the filter in the illumination device, the preamplifier and the ink jet were changed, while the combination mode electronics, the final amplifier and the control electrode were the same.

Finally, some remarks will be made on the choice of a suitable triplet of inks for these experiments. This choice is restricted by many factors. First of all, the ink should not be able to dry in the nozzle when the apparatus is not used even during prolonged periods such as several months. This would clog the nozzle and require a cleaning of the nozzle before the next

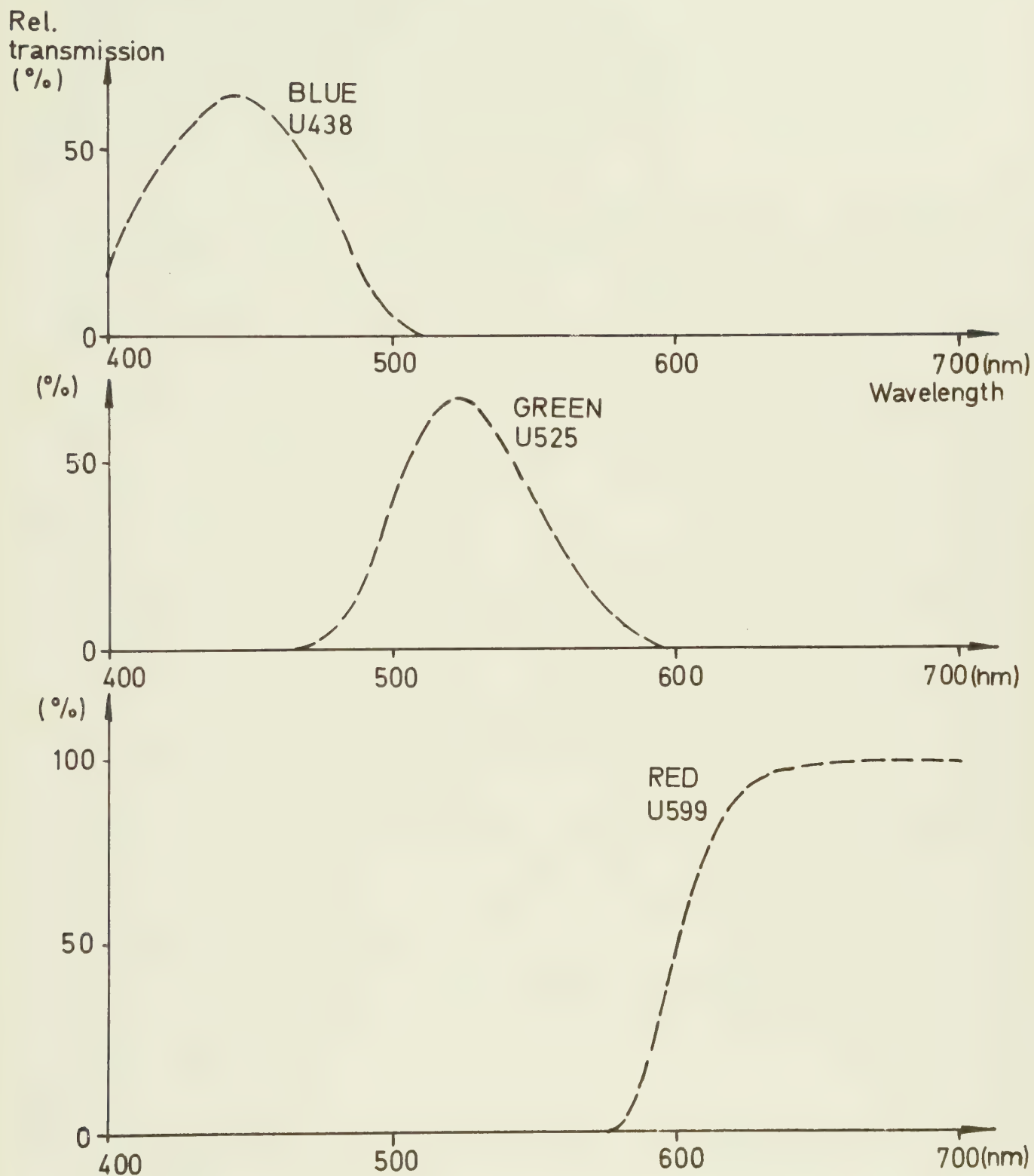


Fig. 8:5. Transmission spectra of colour filters.

reproduction. Further, since the same control electrode E is used for all colours, it is important to avoid the formation of insoluble precipitations in the porous material in the control electrode due to mixing of the inks. Since the different runs are made immediately after each other, always some ink of the colour from the previous run will be present in this material, which might react with the ink deposited in the actual run.

For the quality of the images produced it is also of large importance that the density range created by the different colours is as high as possible. This requirement could be met with a high dye concentration in the inks, which, however, increases the viscosity of the ink above values acceptable by the ink jet device and nearly always leads to drying of the ink in the nozzle when the apparatus is not operated. Here again a compromise between high density and acceptable anti-clogging properties of the ink has to be found. - Finally, for obvious reasons, the relative spectral extinction of the inks should form a colour triplet as ideal as possible.

Many different dyes were investigated with respect to the different parameters mentioned here and a triplet of water soluble dyes supplied by the Bayer AG, Germany, was finally chosen as the best compromise which could be found for inks based on water as a solute. The curves shown in Fig. 8:6 represent the relative spectral extinction of these inks and it is clear from this figure that at least the last of the requirements stated above is not fully met. This is especially true for the cyan dye the extinction of which in the red region of the visible spectrum should be much better which can be seen by comparison with the curves for an ideal colour triplet also given in the figure. Also the partial extinction of blue light by the magenta ink is not desirable. In spite of these defects these inks were chosen for the preliminary experiments since they fulfilled the other demands relatively well. Obviously a much more thorough investigation should be made to find suitable dyes for the present purpose.

8.5.3. Results

In Fig. 8:7 a typical result obtained by colour reproductions with the present apparatus is shown in its natural size. For comparison, the original photographic colour print from which the reproduction was made is also shown in Fig. 8:7 in reduced size. However, when comparing the reproduction with the original it should be pointed out that the technique used to reproduce the

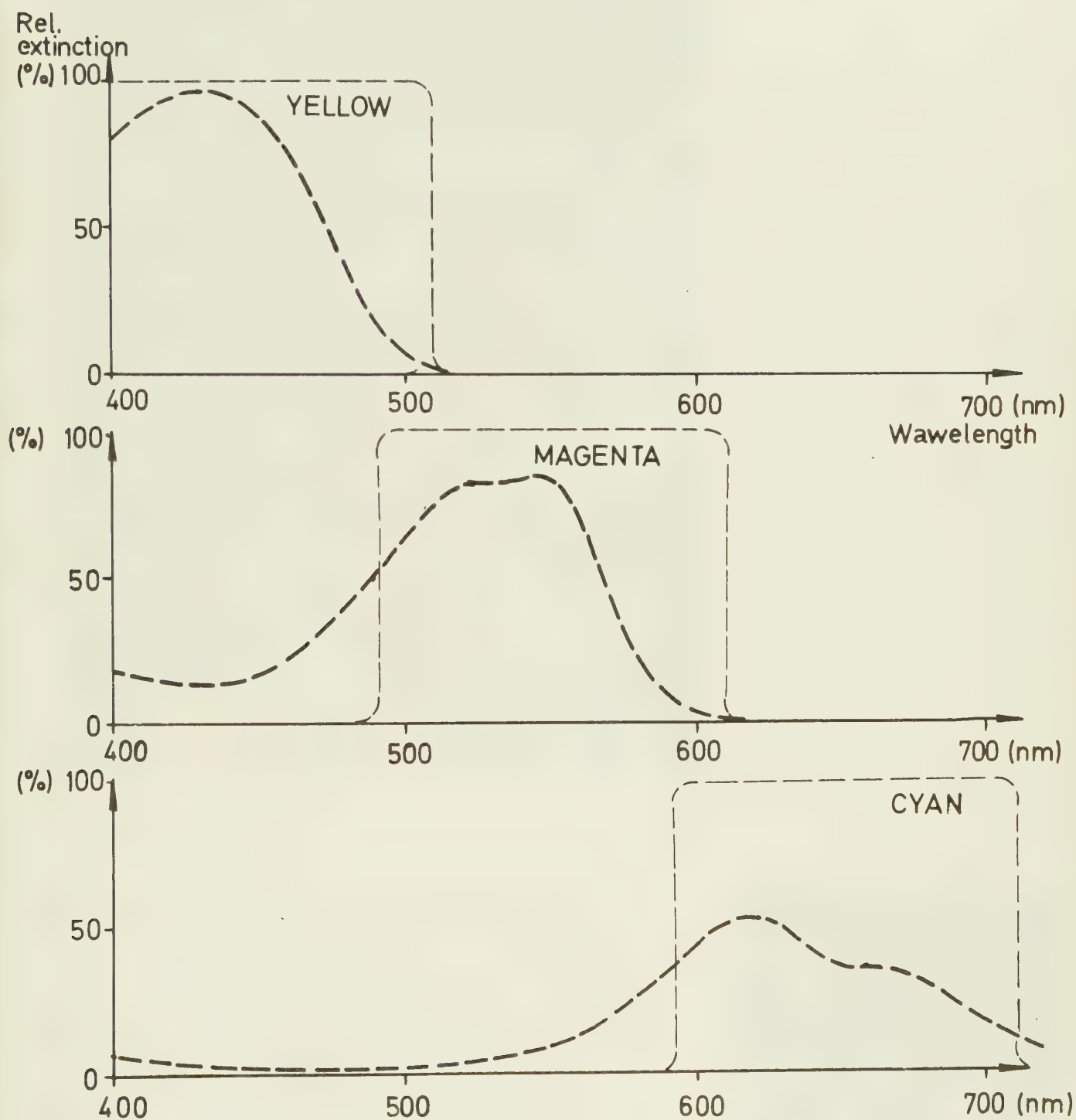


Fig. 8:6. Relative spectral extinction of inks used for colour image reproduction.



a

Fig. 8:7 Colour reproduction in original size(a) ,and original photographic colour print in diminished size (b) .



b



a



b

Fig. 8:8 Magnified print of original (a) and reproduction (b)
of colour image shown in Fig. 8:7.

material shown in the figures introduces an error in colour. Because of these errors the contrast and density range of the ink jet copy seem to be much less than that of the original photograph. Although a definite loss in these image qualities can also be observed in the original material the differences are not as large as indicated by Fig. 8:7. As before it can be found that the density range of the photographic material is approximately 2 for each of the basic colours, while it is only about 1 for colours of the untreated ink jet reproduction. This large difference is partly due to internal multiple reflections of the light at the glossy surface of the gelatine layer of the photographic copy paper which enhances the density range thereby increasing the apparent contrast of the image. In the ink jet reproduction shown in Fig. 8:7 a certain increase in contrast was achieved by the application of a thin highly transparent lacquer layer to the surface of the image after the reproduction process. Even here, a clearly visible enhancement of the contrast can be obtained in this way, which, however, is not as apparent as with the photographic image.

As mentioned before the reproduction was made using three 7 μ m jets with controlled drop formation. An approximate idea of colour ranges obtained with these jets can be obtained from the colour bar pattern which is presented at the bottom of Fig. 8:7. In this pattern, the first and second bar from the left are made by the yellow and magenta jet only, while the last bar to the right was obtained using exclusively the cyan jet. The other bars constitute combinations of these three inks when no intensity modulation was applied to the jets.

Even for this case, magnified prints showing a detail of both the original and the reproduction are presented in Fig. 8:8 to facilitate a closer inspection of the image quality. Again, a millimeter scale is copied together with the pictures to judge the magnification of the prints. In the lower half of Fig. 8:8 a dark coloured object is depicted which was not in focus of the camera when taking the picture. In the green surroundings of this object the transition from the PDM to the voltage mode can be observed nicely as well as the relatively large granularity created by the PDM mode. Further, in the reproduction the direction of the scanning lines can clearly be discerned. Some of the other deficiencies of the reproduction are most readily observed in the little yellow currant in the upper half of the magnified prints. Here the gradual transition between different densities of the red colour is not very well reproduced in the ink jet image. The same is true for the dark lines on the original which seem to have disappeared nearly completely in the reproduction. These defects are caused by imperfections in the many links

used in the present apparatus, e.g., deficiencies in the properties of the electronic circuitry and the unsatisfactory matching between the colour filters in the scanning device and the characteristics of the dyes used in the ink jets. However, the examples shown in Fig. 8:8 do show, that a reasonable quality can be obtained even for colour images by the ink jet method discussed in this paper.

8.6. Other recording surface materials

In the investigations presented so far, different types of papers have been used as record receiving surfaces. However, in many applications it is desirable to transfer images to materials having a much rougher surface texture. Examples for this are sandpaper, corrugated paper, different types of textile fibers etc. Such surfaces do not lend themselves readily to the conventional impact printing, because of which several non-impact printing processes have been developed for this purpose (Childress 1966).

Since the ink jet method studied in this report is a typical exponent for non-impact printing techniques, it was obviously of interest to investigate the capabilities of the method for the printing of surfaces having a rough texture. In the course of this investigation images were reproduced on sandpaper and different types of textiles. Since the results were very similar to each other as well as to the results obtained with ordinary paper, only one example will be described more in detail in the following.

All experiments made with different surface materials were made on the reproduction apparatus shown in Fig. 8:1 using 10 μm diameter nozzles. Thus the drum surface speed was 3 m/s and the line density 10 lines/mm. The record receiving surface was fastened to the drum D_2 in front of the ink jet device in the same way as in the earlier experiments.

Fig. 8:9 shows the result of a three colour print on conventional terry cloth in a slightly diminished scale. It is clear from this figure that the image quality of the reproduction is not markedly reduced compared with a print on normal paper surface in spite of the very rough surface of the terry cloth. This is in good agreement with the results obtained with the other surface materials mentioned above.

This somewhat unexpected result is due to the fact that the ink jet



Fig. 8:9 Colour reproduction on terry cloth.

consists of small drops which hit the recording surface at very high speed. Since these ink drops are very small the ink does not disperse in the absorbing cloth to such an extent that it is visible or deteriorates the image appreciably. Because of the same reason the ink does not penetrate very deeply into the material. Therefore, the reflectance density range obtained in this case is not very much lower than with ordinary paper qualities.

Some faults seem to be detectable in Fig. 8:9. Thus, for example, the red colour in the stalks does not cover the entire space between the sharp black lines defining the boundary of these structures at all places. These details are not due to the reproduction process but were also present in the original used for the generation of the sample.

The result shown here emphasizes the fact that the distance from the ink jet device to the record receiving surface can vary within certain limits without seriously decreasing the quality of the reproduction. Since the ink jet easily travels 6 to 10 cm through air one would expect that distances of this magnitude would still be acceptable. However, it was shown in chapters 2 and 3 that air friction plays an important role for the behaviour of the drops in their flight from the nozzle to the recording surface because of which this distance was to be kept as small as possible to obtain maximum resolution in the images. Therefore, at nozzle to paper distances exceeding 20 to 30 millimeters a serious decline of the image quality is observed. However, in many applications, a variable distance between printing head and the record receiving surface may be of larger importance than image quality, in which instances a suitable compromise between these two quantities can be found.

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